Appendix C

Lake Michigan Air Directors Consortium (LADCO) Interstate Transport Modeling for the 2015 ozone National Ambient Air Quality Standard, Technical Support Document

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LADCO | LAKE MICHIGAN AIR DIRECTORS CONSORTIUM

Interstate Transport Modeling for the 2015 Ozone National Ambient Air Quality Standard

FINAL Technical Support Document

Lake Michigan Air Directors Consortium

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Acknowledgements

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Executive Summary

LADCO prepared this Technical Support Document (TSD) to support the development of the LADCO states' Infrastructure State Implementation Plans (iSIPs) pursuant to the 2015 Ozone National Ambient Air Quality Standard (NAAQS). LADCO used the Comprehensive Air Quality Model with Extensions (CAMx) to support these analyses. The CAMx Anthropogenic Precursor Culpability Assessment (APCA) tool was used to assess the impacts of interstate transport of air pollution on ground level ozone (O_3) concentrations in the Midwest and Northeast U.S. The LADCO CAMx modeling results are used here to identify O_3 monitoring sites that may have nonattainment or maintenance problems for the 2015 O_3 NAAQS in 2023. The modeling outputs are also used to quantify the contributions of emissions in upwind states to surface monitors in downwind states that are projected to have NAAQS attainment problems in 2023. LADCO presents several "flexibilities" in the analytic approaches used to quantify transport and state linkages per a March 2018 U.S. EPA (2018) memo on O_3 transport modeling.

The 2023 emissions data for this study were based on the U.S. EPA 2011v6.3 ("EN") emissions modeling platform (US EPA, 2017b). U.S. EPA generated this platform for their final assessment of Interstate Transport for the 2008 O_3 NAAQS. LADCO replaced the Electricity Generating Unit (EGU) emissions in the U.S. EPA EN platform with 2023 EGU forecasts estimated with the ERTAC EGU Tool version 2.7. ERTAC EGU 2.7 integrated state-reported information on EGU operations and forecasts as of May 2017. Regionally, ERTAC projected lower NOx but higher SO_2 EGU emissions in 2023 in the LADCO states, the Northeast, and Southeast relative to the EPA EN projections. ERTAC EGU projected higher NOx and SO_2 emissions across the CenSARA and WESTAR states relative to the EPA 2023 projections.

The LADCO CAMx simulation predicted that daily maximum 8-hour average (MDA8) O_3 will decrease in 2023 relative to the base year by an average of 5.07 ppbV nationally across all AQS monitors and by an average of 5.95 ppbV across all CASTNet monitors. These changes are similar to the EPA forecasts, which estimated average decreases in MDA8 O_3

of 5.23 ppbV across the AQS monitors and 6.15 ppbV across the CASTNet monitors. In general, the LADCO 2023 CAMx simulation predicted lower O_3 in the Midwest, Northeast, Gulf Coast, and Pacific Coast states relative to the EPA 2023 simulation; the LADCO 2023 CAMx simulation predicted higher O_3 in the Four Corners region and Central Arkansas. The LADCO 2023 CAMx simulation predicted that no monitors in the LADCO region will be nonattainment for the 2015 O_3 NAAQS by 2023. The Kohler Andrae monitor in Sheboygan, WI and the Holland, MI monitors are the only sites in the LADCO region forecasted to be in maintenance for the NAAQS in 2023. Illinois is the highest contributing source region linked to the Sheboygan, WI monitor (14.93 ppbV) followed by WI (9.10 ppbV), IN (6.19 ppbV), MI (1.85 ppbV), and TX (1.76 ppbV). Illinois is the highest contributing source region linked to the Holland, MI monitor as well (19.25 ppbV), followed by IN (6.91 ppbV), MI (3.35 ppV), MS (2.59 ppbV), and TX (2.40 ppbV). While all of the LADCO states, with the exception of MN and WI, have CSAPR-significant linkages to maintenance monitors in the Northeast, OH has the largest single contribution to a monitor outside of the LADCO region (2.83 ppbV at Edgewood, MD).

In addition to the state source region culpability modeling, LADCO developed a CAMx simulation that forecasted the impacts of different inventory sectors on 2023 air quality. The results of this simulation showed that onroad and nonroad mobile sources were consistently the largest contributors to O_3 at the high O_3 monitors in the Midwest and Northeast. Other significant inventory sector contributions at these monitors included EGU point, non-EGU point, and nonpoint sources.

LADCO presents the results from a series of flexibilities for calculating DVs_{2023} and quantifying interstate transport (US EPA, 2018). A LADCO simulation that explored alternative EGU emissions projections forecasted lower DVs_{2023} than the EPA 2023 EN simulation. Three of the six projected nonattainment monitors in the EPA simulation were forecast by the LADCO simulation to be in attainment in 2023. In another analysis, LADCO tested the impacts of excluding model grid cells with land surface coverage that is dominated by water from the DV_{2023} calculation. In general, excluding water cells in the attainment test calculation results in higher DVs_{2023} for the lakeshore monitors in the LADCO region. Finally, in a third analysis, LADCO calculated DVs_{2023} after applying a bias filter to the model results. LADCO filtered the days used for calculating relative reduction factors (RRFs) and DVs_{2023} with a normalized bias threshold of 15%. Instead of calculating RRFs at each monitor from the 10 highest concentration MDA8 O_3 modeled days in the base year, we used the 10 highest days with normalized biases $\leqq$ 15%. Applying the bias filter increased the DVs_{2023} at the Kohler Andrae Sheboygan, WI, Holland, MI, and Bayside Milwaukee, WI monitors; the DV_{2023} at the 7 Mile monitor in Detroit, MI decreased with the application of the bias filter.

1 Introduction

The Lake Michigan Air Directors Consortium (LADCO) was established by the states of Illinois, Indiana, Michigan, and Wisconsin in 1989. The four states and EPA signed a Memorandum of Agreement (MOA) that initiated the Lake Michigan Ozone Study and identified LADCO as the organization to oversee the study. Additional MOAs were signed by the states in 1991 (to establish the Lake Michigan Ozone Control Program), January 2000 (to broaden LADCO's responsibilities), and June 2004 (to update LADCO's mission and reaffirm the commitment to regional planning). In March 2004, Ohio joined LADCO. Minnesota joined the Consortium in 2012. LADCO consists of a Board of Directors (i.e., the State Air Directors), a technical staff, and various workgroups. The main purposes of LADCO are to provide technical assessments for and assistance to its member states, to provide a forum for its member states to discuss regional air quality issues, and to facilitate training for staff in the member states.

One of LADCO's responsibilities is to provide technical air quality modeling guidance and support to the LADCO states. LADCO prepared this Technical Support Document (TSD) to support the development of the LADCO states' Infrastructure State Implementation Plans (iSIPs) pursuant to the 2015 update to the Ozone National Ambient Air Quality Standard (NAAQS).

1.1 Project Overview

LADCO conducted regional air quality modeling to support the statutory obligations of the LADCO states under Clean Air Section 110(a)(2)(D)(i)(i), which requires states to submit "Good Neighbor" SIPs. These SIP revisions are plans to prohibit emissions in one state from interfering with the attainment or maintenance of the NAAQS in another state. LADCO used the Comprehensive Air Quality Model with Extensions (CAMx[1]) to support these analyses. The CAMx Anthropogenic Precursor Culpability Assessment (APCA) tool

[1] www.camx.com

was used to assess the impacts of interstate transport of air pollution on ground level ozone (O_3) concentrations in the Midwest and Northeast U.S.

In support of previous rulemakings (CSAPR, 2011; CSAPR Update, 2016), the U.S. EPA in partnership with states developed a four-step interstate transport framework to address the "Good Neighbor" provisions of the O_3 and $PM_{2.5}$ NAAQS. This framework established the following four steps to identify and mitigate high O_3 concentrations at locations that were at risk of violating the NAAQS in the future: (1) identify monitors with predicted air quality problems in the future year; (2) identify the upwind states that are "linked" through air mass transport to the problem monitors; (3) identify emissions reductions necessary to prevent upwind states from contributing significantly to NAAQS violations at a downwind monitor; and (4) adopt permanent and enforceable measures needed to achieve the identified emissions reductions. Recently, EPA (2018) issued a memo describing a series of potential flexibilities in this four-step framework that states could consider in developing a transport SIP.

LADCO used CAMx to predict O_3 concentrations in 2023 to address steps (1) and (2) of the four-step Interstate Transport framework. These flexibilities included a comparison between EPA and LADCO CAMx modeling for 2023, exploring the impacts of including or removing water cells in the calculation of future design values, and exploring the influence of model bias on calculating future design values. All of the alternative analyses presented here are in the context of establishing links between an upwind state and downwind nonattainment or maintenance problems at surface O_3 monitors in the Midwest and Northeast U.S.

This document describes how LADCO used CAMx source apportionment modeling to link upwind and downwind states and to identify upwind emissions sources that significantly contribute to downwind NAAQS attainment issues. The CAMx APCA modeling outputs of this work are being presented to the LADCO states to support the "Good Neighbor" SIP provisions of their 2015 O_3 NAAQS Infrastructure SIPs (iSIP) that are due to EPA in October 2018.

1.2 Organization of the Technical Support Document

This technical support document (TSD) is presented to the LADCO states for estimating year 2023 O_3 design values and source-receptor relationships using the CAMx APCA technique. The TSD is organized into the following sections. Section 2 describes the 2023 Air Quality Modeling Platform that LADCO used to forecast 2023 O_3. Section 3 describes the approach used for estimating Future Ozone Design Values. This section also includes a discussion on the methods used for identifying sites that are forecast to have O_3 NAAQS attainment problems. Section 4 describes the Ozone Source Apportionment modeling used to link source regions with problem monitors in the future year. Section 5 presents a Discussion of Modeling Results that the LADCO states can use to support their 2015 O_3 NAAQS Good Neighbor SIPs. This last section includes the following results:

- LADCO benchmarking of the U.S. EPA modeling platform on the LADCO computing system;
- Future year O_3 forecasts from the LADCO CAMx modeling;
- Interstate transport linkages estimated with the LADCO forecasts;
- Alternative attainment test results of future year design values computed with different analysis flexibilities

The TSD concludes with a summary of Significant Findings and observations from the LADCO modeling, including on the quantification of interstate O_3 transport and establishing linkages between source regions and possible O_3 NAAQS attainment problems in 2023.

2 2023 Air Quality Modeling Platform

LADCO based our 2023 O_3 air quality and Interstate Transport forecasts on the CAMx modeling platform released by the U.S. EPA in October 2017 in support of the Interstate Transport SIPs for the 2008 O_3 NAAQS (US EPA, 2017). The U.S. EPA 2023EN modeling platform was projected from a 2011 base year and included a complete set of CAMx inputs, including meteorology, initial and boundary conditions, and emissions data. The future year, or 2023, component of the air quality modeling platform refers to the emissions data only. All other CAMx inputs, including the meteorology data simulated with the Weather Research Forecast (WRF) model, represented year 2011 conditions. LADCO used the majority of the data and software provided by U.S. EPA for this platform, with a few exceptions described below.

2.1 Modeling Year Justification

LADCO selected 2011 as a modeling year for this study because CAMx input data for 2011 were widely available and relatively well-evaluated. 2011 had also been identified as a good year for studying O_3 in the Eastern U.S. The U.S. EPA (2015) noted that year 2011 meteorology in the Eastern U.S., including the LADCO region, was warmer and drier than the climatic norm. As compared to other recent years, the summer of 2011 represented typical conditions conducive to high observed O_3 concentrations in the Midwest and Northeast U.S.

Figure 1 shows the 2009-2013 base year O_3 design values for the modeling period selected for this study. Each bubble on the plot represents a U.S. EPA Air Quality System (AQS) O_3 surface monitor. Orange, red, and purple colors indicate monitors that were nonattainment ($\geqq$71.0 ppbV) for the 2015 O_3 NAAQS during this period. High O_3 concentrations were observed throughout the domain, with particularly high values along the Lake Michigan shoreline, St. Louis, southern Indiana, and the Northeast Corridor from Washington D.C. to Connecticut.

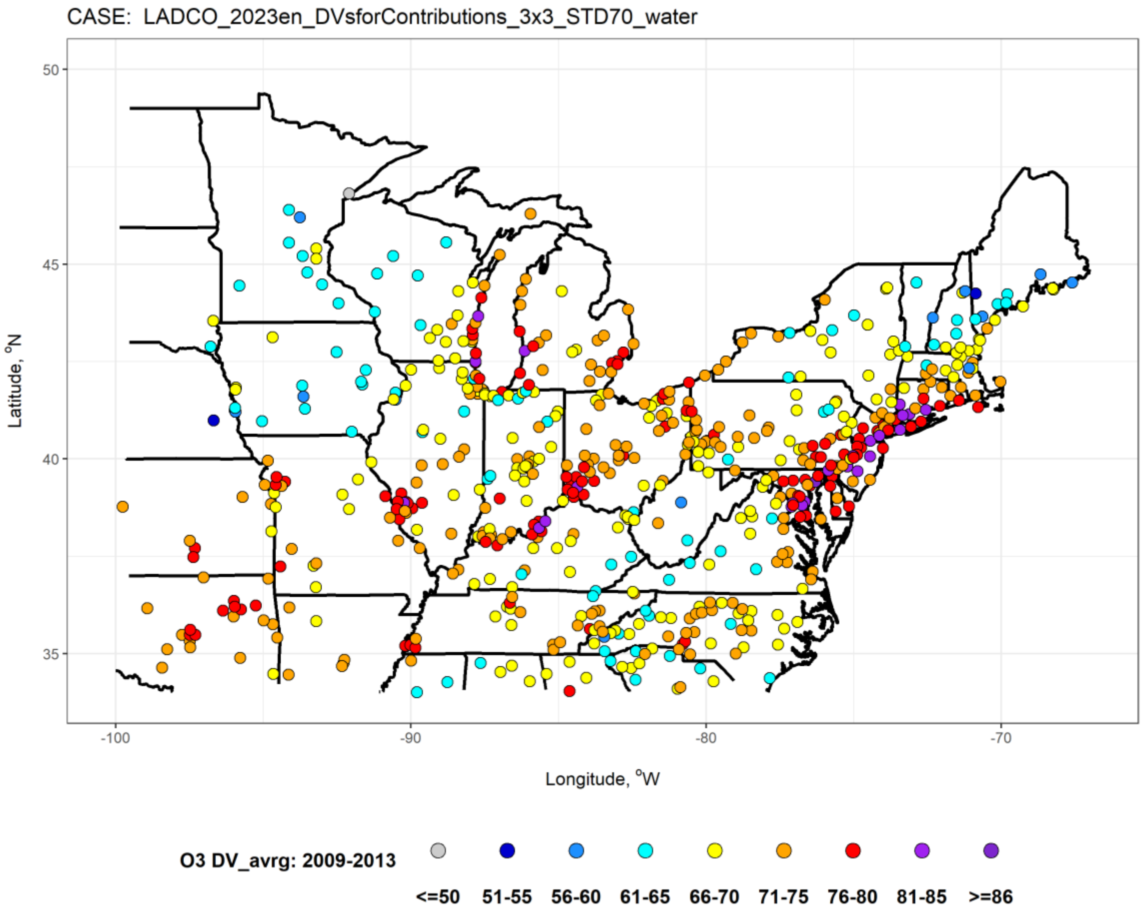

Figure 1. 2011 (2009-2013) O_3 design values for the eastern U.S.

The triennial National Emissions Inventory (NEI) synchronized with 2011. Since its first release in 2014, the NEI2011 has undergone several revisions, with the most recent updates to version 6.3 released in October 2017 as part of the U.S. EPA's final 2008 O_3 NAAQS interstate transport assessment (US EPA, 2017). The 2011-based emissions modeling platforms are currently the best available national-scale datasets for simulating air quality in the U.S. The U.S. EPA used version 6.3 of the NEI2011-based emissions modeling platform for their preliminary assessment of O_3 transport for the 2015 O_3 NAAQS (US EPA, 2016). Given recent use of 2011-based data for evaluating interstate transport by the U.S. EPA and the lack of a more contemporary national emissions modeling platform, LADCO believes that using 2011-based data and emissions projections are justified for assessing interstate O_3 transport.

LADCO selected 2023 as the future projection year based on the availability of data from U.S. EPA. U.S. EPA selected 2023 for 2015 O_3 NAAQS modeling because it "aligns with the anticipated attainment year for moderate O_3 nonattainment areas" (US EPA, 2018).

2.2 Air Quality Model Configuration

LADCO based the CAMx air quality modeling platform for this study on the configuration that the U.S. EPA used to support both their October 2017 memo on Interstate Transport SIPs for the 2008 O_3 NAAQS (US EPA, 2015) and their December 2016 technical support document on a preliminary assessment of Interstate Transport for the 2015 O_3 NAAQS (US EPA, 2016). LADCO used CAMx v6.40 (Ramboll-Environ, 2016) as the photochemical grid model for this study. CAMx is a three-dimensional, Eulerian air quality model that simulates the chemical transformation and physical transport processes of air pollutants in the troposphere. It includes capabilities to estimate the concentrations of primary and secondary gas and particle phase air pollutants, and dry and wet deposition, from urban to continental spatial scales. As CAMx associates source-level air pollution emissions estimates with air pollution concentrations, it can be used to design and assess emissions reduction strategies pursuant to NAAQS attainment goals.

LADCO selected CAMx for this study because it is a component of recent U.S. EPA modeling platforms for investigating the influence of interstate transport on O_3, and because it has source apportionment capabilities for quantifying air pollution source-receptor relationships. As CAMx is a component of U.S. EPA studies with a similar scope to this project, LADCO was able to leverage the data and software elements that are distributed with U.S. EPA regulatory modeling platforms. Using these elements saved LADCO significant resources relative to building a modeling platform from scratch. CAMx is also instrumented with source apportionment capabilities that allowed LADCO to investigate the sources of air pollution impacting O_3 monitors within and downwind of the LADCO region.

Figure 2 shows the U.S. EPA transport modeling domain for the continental U.S. A 12-km uniform grid (CONUS12) covers all of the continental U.S. and includes parts of Southern Canada and Northern Mexico. The domain has 25 vertical layers with a model top at about

17,550 meters (50 mb). LADCO used the same U.S. EPA 12-km domain for this project because it supported the use of meteorology, initial and boundary conditions, and emissions data that were freely available from U.S. EPA.

As the focus of this study is on O_3, LADCO used CAMx to simulate the O_3 season. LADCO simulated May through October 1, 2011 as individual months using 10-day model spin-up periods for each month.

U.S. EPA (2016) provided completed details their 2011 CAMx simulation, including a performance evaluation.

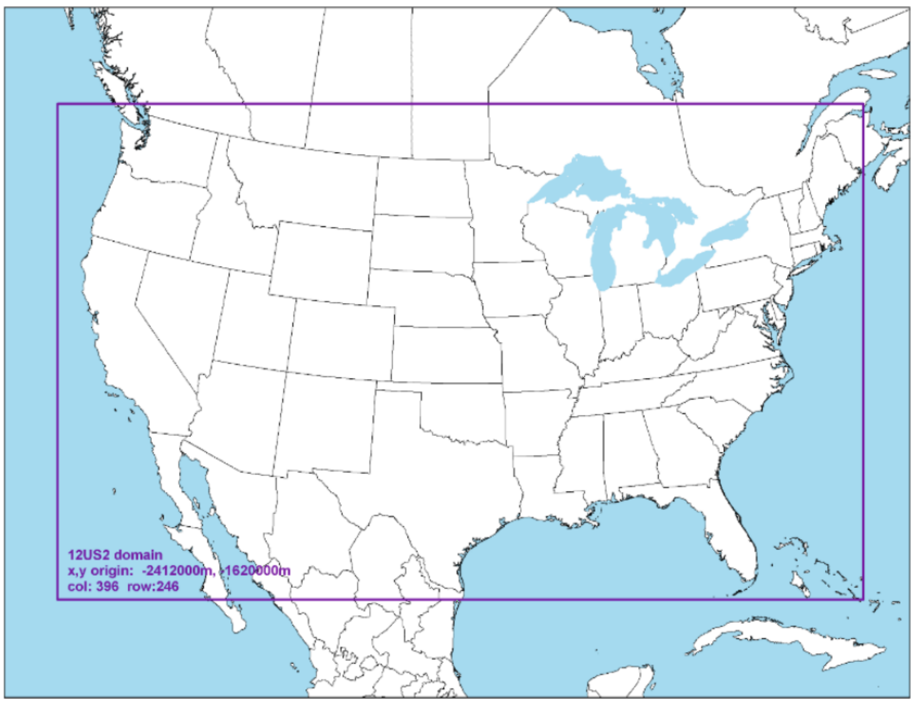

Figure 2. CAMx 12-km modeling domain (CONUS12)

2.3 Meteorology Data

LADCO used the U.S. EPA 2011 WRF data for this study (US EPA, 2017). The U.S. EPA used version 3.4 of the WRF model, initialized with the 12-km North American Model (NAM) from the National Climatic Data Center (NCDC) to simulate 2011 meteorology. Complete details of the WRF simulation, including the input data, physics options, and four-dimensional data assimilation (FDDA) configuration are detailed in the U.S. EPA

2008 Transport Modeling technical support document (US EPA, 2015). U.S. EPA prepared the WRF data for input to CAMx with version 4.3 of the WRFCAMx software.

2.4 Initial and Boundary Conditions

LADCO used 2011 initial and boundary conditions for CAMx generated by the U.S. EPA from the GEOS-Chem Global Chemical Transport Model (US EPA, 2017). EPA generated hourly, one-way nested boundary conditions (i.e., global-scale to regional-scale) from a 2011 2.0 degree x 2.5 degree GEOS-Chem simulation. Following the convention of the U.S. EPA O_3 transport modeling, year 2011 GEOS-Chem boundary conditions were used by LADCO for modeling 2023 air quality with CAMx.

2.5 Emissions Data

The 2023 emissions data for this study were based on the U.S. EPA 2011v6.3 (“EN”) emissions modeling platform (US EPA, 2017b). U.S. EPA generated this platform for their final assessment of Interstate Transport for the 2008 O_3 NAAQS. Updates from earlier 2011-based emissions modeling platforms included a new engineering approach for forecasting emissions from Electricity Generating Units (EGUs). While the U.S. EPA made several changes to the forecasted 2023 emissions in the “EN” platform relative to the earlier “EL” platform, the changes to the base year (2011) model between the two platforms were minor (US EPA, 2017b).

LADCO replaced the EGU emissions in the U.S. EPA EN platform with 2023 EGU forecasts estimated with the ERTAC EGU Tool version 2.7[2]. ERTAC EGU 2.7 integrates state-reported information on EGU operations and forecasts as of May 2017. The ERTAC EGU Tool provided more accurate estimates of the growth and control forecasts for EGUs in the Midwest and Northeast states than the U.S. EPA approach used for the “EN” platform. LADCO used the U.S. EPA EN Platform emissions estimates for all other inventory sectors.

[2] http://www.marama.org/2013-ertac-egu-forecasting-tool-documentation

2.5.1 Electricity Generating Unit Emissions

The ERTAC EGU model for growth was developed around activity pattern matching algorithms designed to provide hourly EGU emissions data for air quality planning. The original goal of the model was to create low-cost software that air quality planning agencies could use for developing EGU emissions projections. States needed a transparent model that was numerically stable and did not produce dramatic changes to the emissions forecasts with small changes in inputs. A key feature of the model includes data transparency; all of the inputs to the model are publicly available. The code is also operationally transparent and includes extensive documentation, open source code, and a diverse user community to support new users of the software.

Operation of the model is straightforward given the complexity of the projection calculations and inputs. The model imports base year Continuous Emissions Monitoring (CEM) data from U.S. EPA and sorts the data from the peak to the lowest generation hour. It applies hour specific growth rates that include peak and off peak rates. The model then balances the system for all units and hours that exceed physical or regulatory limits. ERTAC EGU applies future year controls to the emissions estimates and tests for reserve capacity, generates quality assurance reports, and converts the outputs to SMOKE ready modeling files.

ERTAC EGU has distinct advantages over other growth methodologies because it is capable of generating hourly future year estimates which are key to understanding O_3 episodes. The model does not shutdown or mothball existing units because economics algorithms suggest they are not economically viable. Additionally, alternate control scenarios are easy to simulate with the model. Full documentation for the ERTAC Emissions model and 2.7 simulations are available through the MARAMA website[2].

Differences between the EPA and ERTAC EGU emissions forecasts arise from alternative forecast algorithms and from the data used to inform the model predictions. The U.S. EPA EGU forecast used in the 2023 EN modeling used CEM data available through the end of 2016 and comments from states and stakeholders received through April 17, 2017 (US EPA, 2017). ERTAC EGU 2.7 used CEM data from 2011 and state-reported changes to EGUs through May 2017. The ERTAC EGU 2.7 emissions used for the modeling reported in this TSD represent the best available information on EGU forecasts for the Midwest and Eastern U.S. available during Spring-early Summer 2018.

2.5.2 LADCO 2023 Emissions Summary

The tables and figures in this section summarize the emissions used in the LADCO and EPA 2023 CAMx simulations. Table 1 shows the annual total NOx, SO_2, and volatile organic compound (VOC) EGU emissions for the base year (2011), ERTAC EGU 2023, and the U.S. EPA EN 2023 inventories. Table 2 presents the total 2023 O_3 season (May 1 – September 30) emissions for the major criteria pollutants. LADCO state and regional total emissions are presented in both of these tables. Figure 3 through Figure 8 graphically summarize the EGU NOx, SO_2, and VOC emissions for the LADCO states and MJO regions. The ERTAC EGU 2023 and U.S. EPA EN 2023 EGU emissions estimates differ across the LADCO states. Where ERTAC estimates higher future year NOx emissions than the EPA projection in Illinois, Ohio, and Wisconsin, it estimates lower emissions in the other LADCO states. ERTAC projects higher future year SO_2 emissions than the EPA for Illinois, Indiana, Ohio, and Wisconsin. [Add discussion on VOC projections].

Regionally, ERTAC projects higher NOx emission than EPA in the LADCO states, the southeast, and west. ERTAC EGU projects higher SO_2 in all regions of the country relative to the U.S. EPA 2023 projections. [Add discussion on VOC projections].

While these annual summaries mask the fine scale temporal differences between the EGU projection methodologies, in general the differences in O_3 projections between the LADCO and U.S. EPA simulations (Section 5.5.1,) are consistent with the differences in annual total NOx emissions between the EGU projections used in each simulation. The LADCO 2023 simulation generally forecasted lower O_3 in the Northeast than the U.S. EPA 2023 EN simulation, consistent with the lower EGU NOx emissions predicted by ERTAC EGU in this region. The higher NOx emissions projections in the LADCO simulation for the Southeast and West manifested in hotspots of high ozone in the these regions.

Total 2023 O_3 season emissions are presented in Table 2 as a record of the emissions used in the LADCO 2023 CAMx simulation.

Table 1. EGU sector emissions annual NOx and SO_2 totals (tons/year)

State/ Region	NEIv6.3 2011			ERTAC2.7 2023			U.S. EPA EN 2023		
	NOx	SO2	VOC	NOx	SO2	VOC	NOx	SO2	VOC
LADCO States									
IL	73,644	227,288	1,602	34,078	81,899	1,459	30,764	73,747	1,155
IN	120,264	356,326	1,797	61,314	114,865	1,665	63,397	80,472	1,327
MI	77,739	229,654	1,142	27,977	43,818	868	33,708	67,252	910
MN	35,181	40,800	694	14,600	14,904	596	21,919	15,606	594
OH	103,189	593,343	1,503	50,140	114,289	1,060	37,573	89,933	894
WI	31,702	92,179	714	15,829	10,826	668	15,419	7,623	640
Regional Totals									
LADCO	441,719	1,539,590	7,453	203,938	380,601	6,516	202,760	334,634	5,521
MARAMA/ OTC	276,045	554,351	4,016	84,533	197,712	4,406	118,007	121,276	4,334
SESARM	468,394	1,126,779	11,193	291,058	320,508	9,236	261,551	241,046	9,958
CENSARA	513,158	1,110,171	10,038	274,253	624,243	9,062	288,122	503,746	7,756
WESTAR	331,503	302,332	5,267	298,107	234,680	3,485	164,896	127,358	5,028

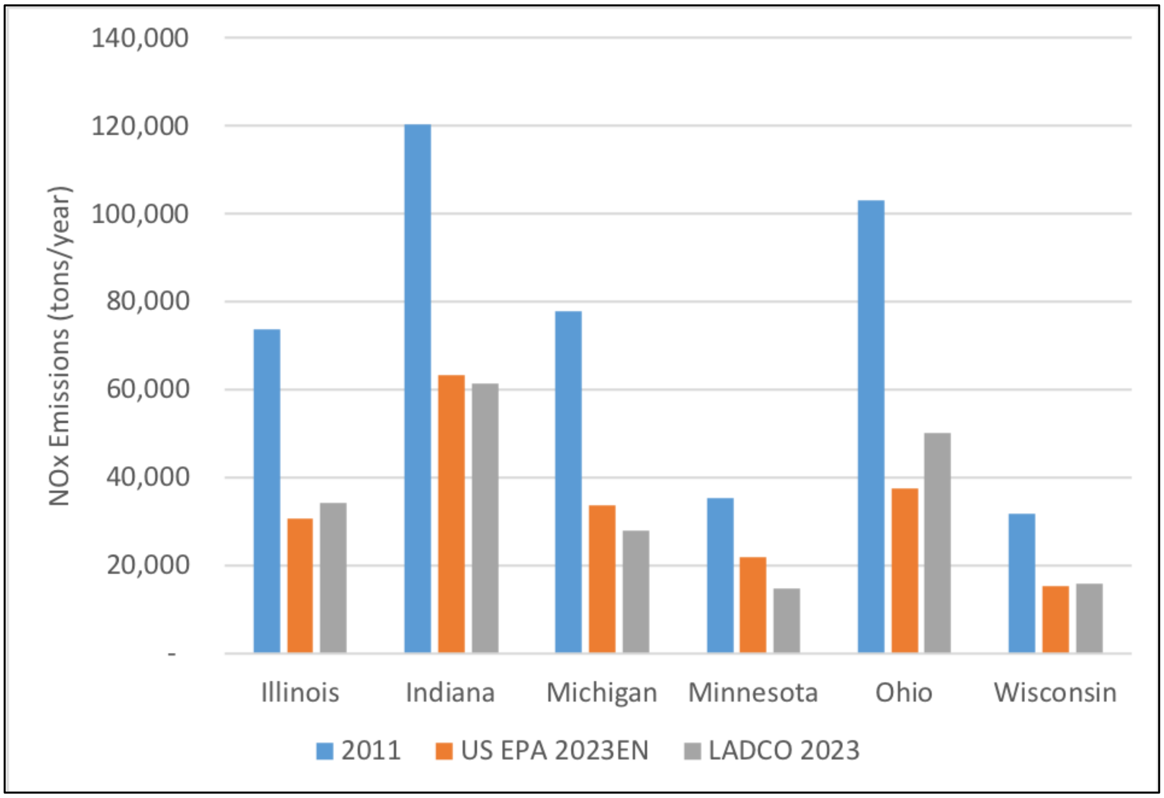

Figure 3. EGU NOx emissions comparison – LADCO state annual totals (tons/year)

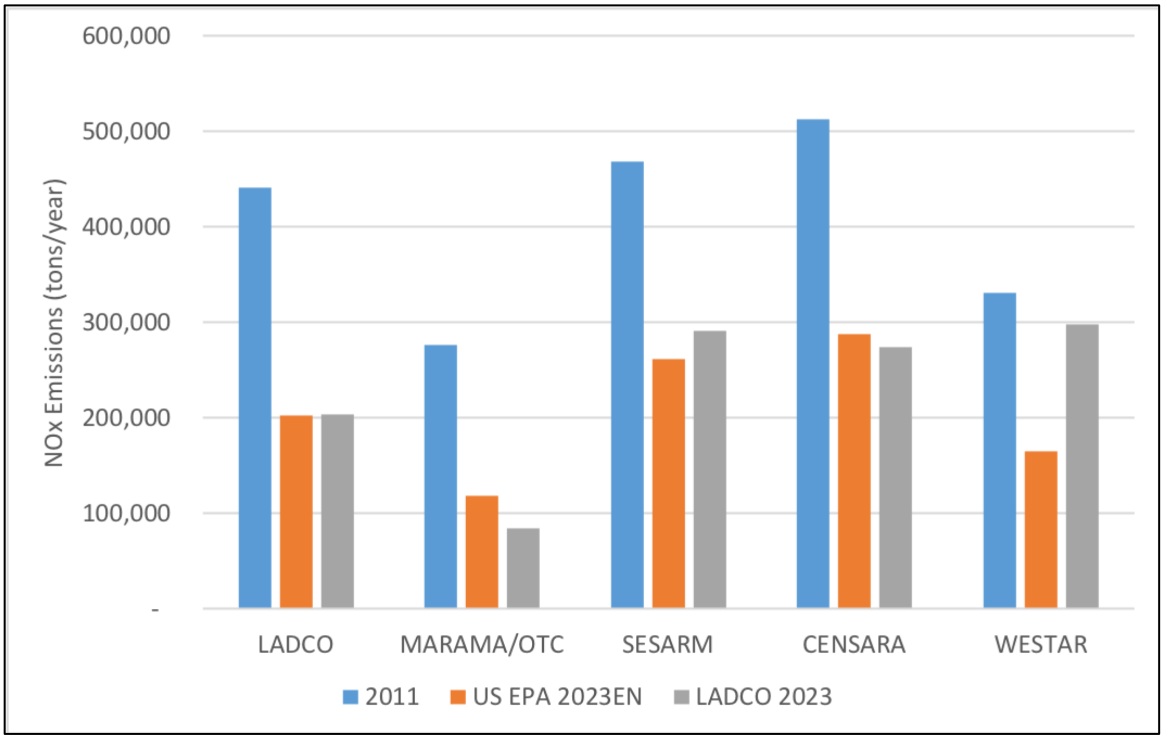

Figure 4. EGU NOx emissions comparison – MJO annual totals (tons/year)

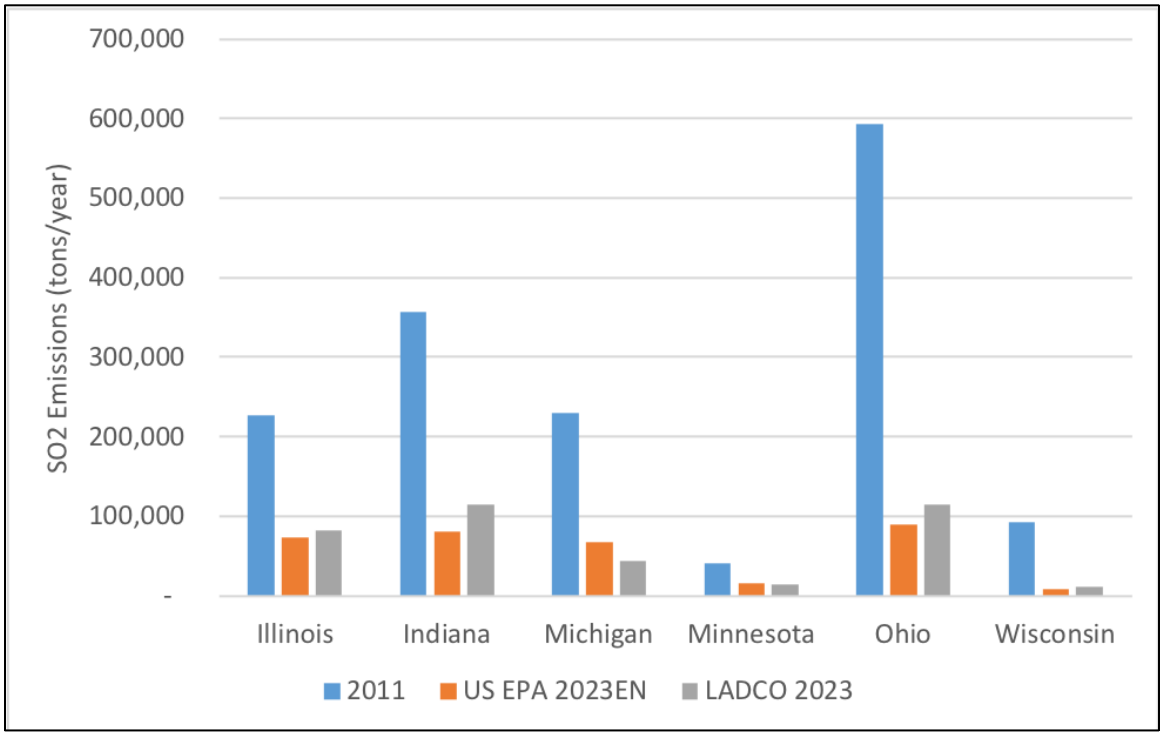

Figure 5. EGU SO_2 emissions comparison – LADCO state annual totals (tons/year)

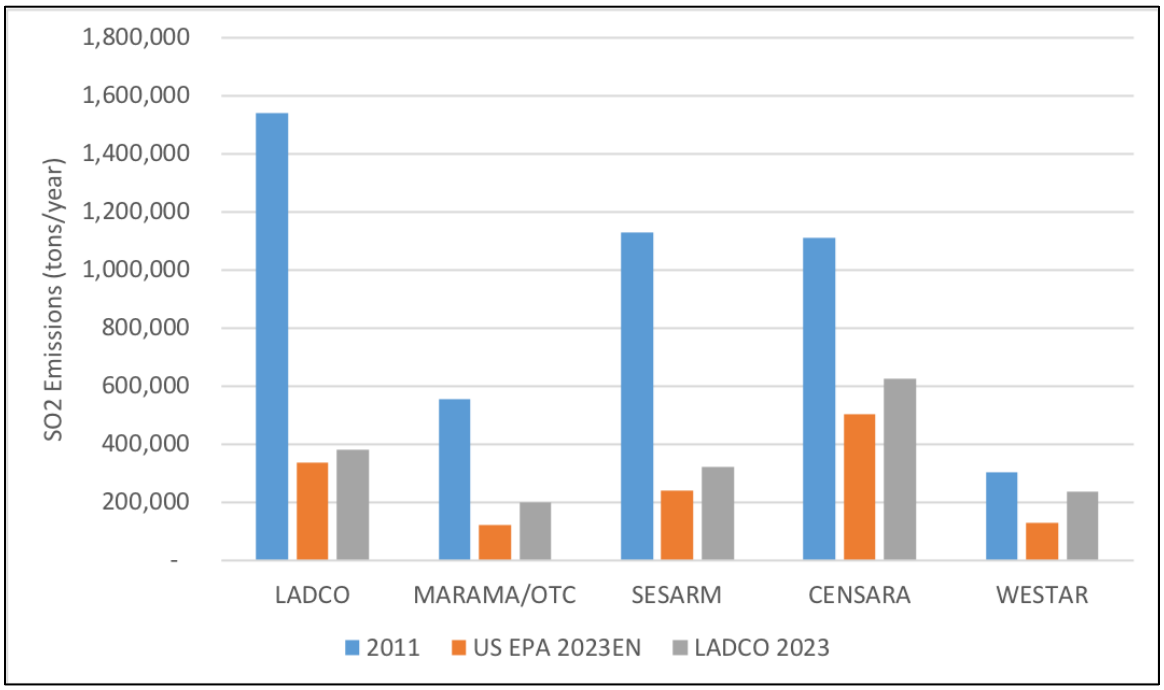

Figure 6. EGU SO_2 emissions comparison – MJO annual totals (tons/year)

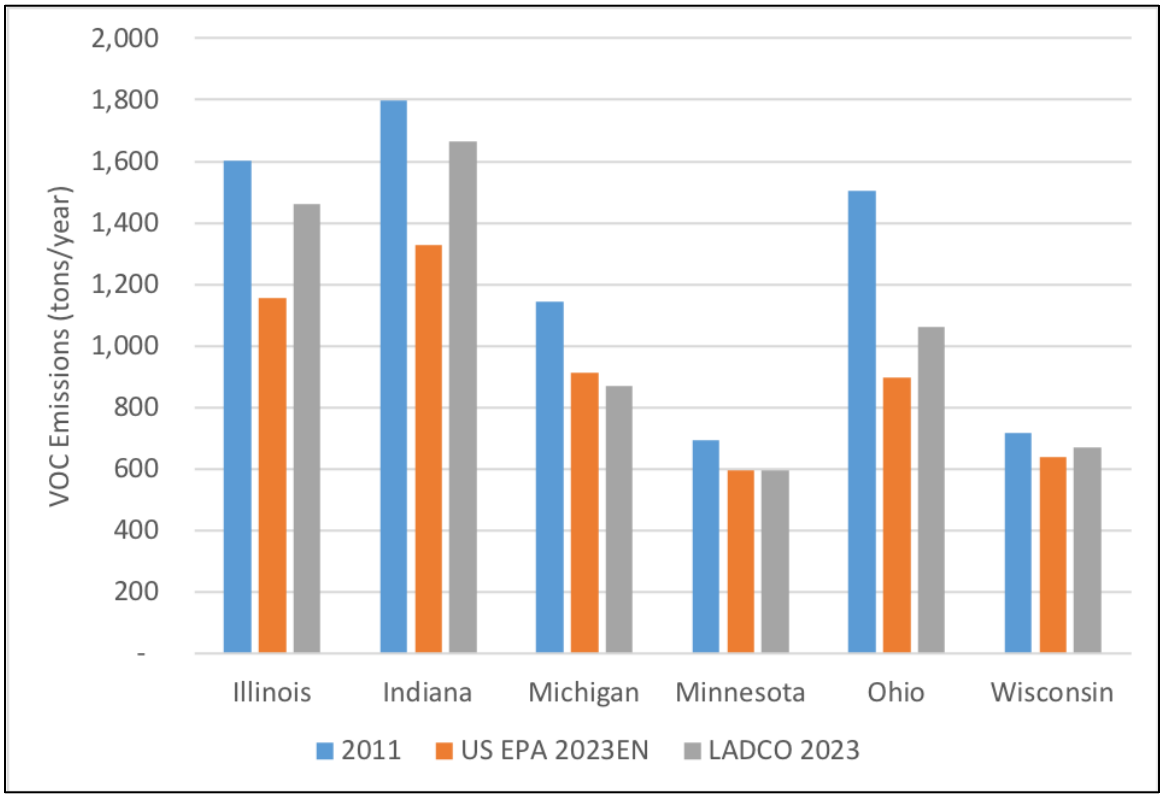

Figure 7. EGU VOC emissions comparison – LADCO state annual totals (tons/year)

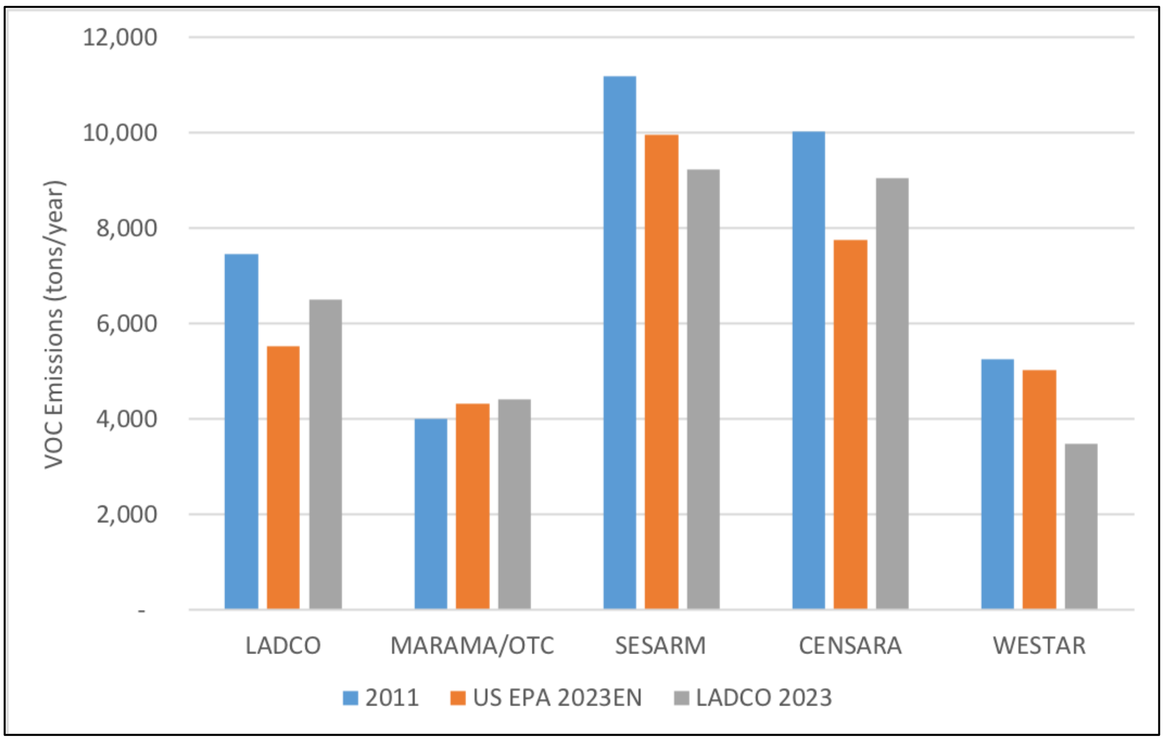

Figure 8. EGU VOC emissions comparison – MJO annual totals (tons/year)

Table 2. Total O_3 season emissions for the LADCO 2023 simulations (tons/season)

State/ Region	CO	NOx	VOC	SO_2	NH_3	$PM_{2.5}$
LADCO States						
IL	607,125	143,052	497,088	44,492	47,348	41,223
IN	513,679	110,536	327,044	65,725	61,564	28,785
MI	632,948	102,683	609,349	43,644	39,374	25,621
MN	984,896	95,232	661,274	16,987	103,977	82,507
OH	687,300	115,544	424,614	58,947	62,778	32,843
WI	417,474	69,094	504,084	13,832	74,005	20,940
Region Totals						
LADCO	3,843,423	636,140	710,178	243,628	389,046	231,919
MARAMA OTC	2,635,608	503,960	435,648	123,407	115,592	77,799
SESARM	7,159,486	974,250	1,052,772	294,760	442,054	420,764
CENSARA	5,046,349	903,500	1,631,140	289,903	635,259	390,384
WESTAR	10,584,500	1,289,397	2,404,757	179,681	709,998	778,381

2.6 U.S. EPA Modeling Platform Benchmarking

LADCO benchmarked both the U.S. EPA 2011 and 2023 CAMx "EN" modeling platforms on our computing cluster. The benchmark simulation used the exact same CAMx version and configuration as was used by U.S. EPA. The purpose of these simulations was to confirm that LADCO correctly installed and configured the U.S. EPA data and software on our cluster. We needed to verify our installation of the modeling platform on the LADCO computing cluster in order to take advantage of the extensive vetting and evaluation of the platform by U.S. EPA. By reproducing the U.S. EPA CAMx modeling results on the LADCO servers, we inherited the model evaluation completed by the U.S. EPA, thereby validating the use of the platform for this study.

LADCO verified the platform installation on our computing systems by comparing the results of the U.S. EPA and LADCO 2011 and 2023 EN simulations. We simulated the entire O_3 season, with spin up, for both 2011 and 2023 for comparison with the U.S. EPA modeling. The LADCO benchmarking results for the 2011 simulation are presented in Section 5.1.

2.7 Evaluation of the LADCO 2023 CAMx Simulation

As future year air quality forecasts cannot be compared to observations for evaluation, LADCO relied on the model performance evaluation (MPE) conducted by the U.S. EPA on the base modeling platform that we used for this study (US EPA, 2016) to establish validity in the modeling platform. In addition to the MPE for the base year CAMx simulation, the U.S. EPA reported full MPE results for the 2011 WRF modeling (US EPA, 2014) used to drive the CAMx simulations.

LADCO compared the 2023 O_3 forecasts that we generated in this study against the 2023 U.S. EPA “EN” platform results. We compared daily average and daily maximum 1-hour and 8-hour O_3 concentrations at monitoring locations in the Midwest and Northeast. The purpose of this comparison was to evaluate the changes in the LADCO forecasts that result from the change in the EGU emissions forecasts used for this study relative to the U.S. EPA 2023 modeling. The comparisons of the 2023 O_3 forecasts for the LADCO and U.S. EPA CAMx simulations are presented in Section 5.2.

3 Future Year Ozone Design Values

LADCO followed the U.S. EPA Draft Guidance for Attainment Demonstration Modeling (US EPA, 2014b) to calculate design values in 2023 (DV_{2023}) for monitors in the Midwest and Northeast U.S. As we used a base year of 2011, we estimated the base year design values using surface observations for the years 2009-2013 ($DV_{2009-2013}$). LADCO estimated the DV_{2023} with version 1.2 of the Software for Modeled Attainment Test Community Edition (SMAT-CE)[3]. SMAT-CE was configured to use the average O_3 concentration in a 3x3 matrix around each monitor across the 10 highest modeled days, per the U.S. EPA Guidance.

SMAT-CE uses a four step process to estimate DVs_{2023}:

1. Calculate $DV_{2009-2013}$ for each monitor
    - The O_3 design value is a three-year average of the 4th highest daily maximum 8 hour average O_3 ($MDA8_4$):

$$DV_{2011} = (MDA8_{4,2009} + MDA8_{4,2010} + MDA8_{4,2011})/3$$

    - Weighted 5-year average of design values centered on the base model year (2011):

$$DV_{2009-2013} = (DV_{2011} + DV_{2012} + DV_{2013})/3$$

2. Find highest base year modeled days surrounding each monitor
    - Find ten days with the highest base year modeled MDA8 from within a 3x3 matrix of grid cells surrounding each monitor
    - At least 5 days with modeled MDA8 >= 60 ppb are needed to retain the monitor for the future year DV calculation
3. Calculate relative response factor (RRF) for each monitor
    - Calculate averaged MDA8 for the base and future years from the average of the values in the 3x3 matrix in each of the selected top 10 modeled days
    - Calculate the RRF as the ratio of the future to base year averaged MDA8:

$$RRF = MDA8_{2023,avg}/MDA8_{2011,avg}$$

[3] https://www.epa.gov/scram/photochemical-modeling-tools

4. Calculate DV_{2023} for each monitor

$$DV_{2023} = RRF * DV_{2009\text{-}2013}$$

Following from the U.S. EPA March 2018 Ozone Transport Memo, we also calculated DVs_{2023} to account for the influence of surface water on CAMx performance over coastal regions. The alternative DV_{2023} calculation approach presented by U.S. EPA excludes from the 3x3 matrix around a monitor those model grid cells that are dominated by water (> 50% water by landuse coverage). In the case of water-dominated grid cells that include a monitor, the monitor cell is included in the alternative calculation. Additional details of the U.S. EPA approaches that LADCO used for calculating DV_{2023} are provided in the U.S. EPA's Ozone Transport Modeling Assessments (US EPA 2018; US EPA, 2016; US EPA, 2015).

LADCO employed another alternative for calculating DV_{2023} that considers the skill of CAMx in reproducing the base year observations near a monitor. The standard U.S. EPA DV_{2023} approach uses the ten modeled days with the highest MDA8 concentrations around a monitoring location to estimate the relative response factor (RRF) for a monitor. In this approach, the top ten days are selected irrespective of the ability of the model to reproduce the observations during the selected days.

Table 3 illustrates an example of the MDA8 modeled and observed concentrations at the Chiwaukee Prairie, WI monitor on the top 10 modeled days from the LADCO 2011 CAMx simulation. The table shows that 6 of the top 10 modeled days correspond with days that are in the top 10 observed days (yellow shading); two of the top 10 modeled days are in the top 11-20 observed days (orange shading). Four of the top 10 modeled days also have percent biases greater than 15%, with one day exhibiting a model overprediction of greater than 134%.

Table 3. Chiwaukee Prairie, WI (AQS ID: 550590019) top 10 modeled MDA8 days

Date	OBS*	MOD*	BIAS*	NORM BIAS
7/4/2011	79.25	105.63	26.38	33.29%
7/9/2011	83.00	101.03	18.03	21.72%
7/24/2011	41.63	97.69	56.06	134.69%
7/30/2011	51.75	91.22	39.47	76.26%
9/1/2011	96.00	91.21	-4.79	4.99%
7/17/2011	88.25	82.95	-5.30	6.01%
7/10/2011	77.38	78.89	1.52	1.96%
7/23/2011	74.88	77.36	2.49	3.32%
6/7/2011	68.38	73.93	5.55	8.12%
9/2/2011	71.13	73.75	2.62	3.69%

*Units = ppbV; BIAS = MOD-OBS; NORM BIAS = (MOD-OBS)/OBS

The alternative DFV calculation explored by LADCO filtered the model results by bias, selecting the top 10 model days only from days when the bias falls below a certain threshold. As the U.S. EPA Modeling Guidance (2014b) sets the model performance goal for O_3 at 15% normalized mean bias, LADCO excluded days with a bias greater than 15% in an alternative "bias filtered" DV_{2023} calculation.

Table 4 extends the example for the Chiwaukee Prairie, WI monitor by showing the top 10 modeled days with absolute modeled bias less than or equal to 15%. Filtering out the high bias days results in all of the top 10 modeled days corresponding to days in which the observations were in the top 20 concentrations of all days. With this approach, not only are more of the highest concentration observed days included in the RRF calculation but the days that are included will be those in which the model was able to better reproduce the observations. In exhibiting better skill on these days, the model has a better chance of capturing the causes of the high O_3 and subsequently simulating the sensitivity of changes in emissions on the O_3 concentrations.

Table 4. Chiwaukee Prairie, WI top 10 modeled MDA days with bias <= 15%

Date	OBS	MOD	BIAS*	NORM BIAS
9/1/2011	96.00	91.21	-4.79	4.99%
7/17/2011	88.25	82.95	-5.30	6.01%
7/10/2011	77.38	78.89	1.52	1.96%
7/23/2011	74.88	77.36	2.49	3.32%
6/7/2011	68.38	73.93	5.55	8.12%
9/2/2011	71.13	73.75	2.62	3.69%
8/31/2011	70.38	72.49	2.12	3.01%
6/6/2011	75.29	71.73	-3.56	4.73%
8/2/2011	75.50	69.47	-6.03	7.98%
7/15/2011	65.75	67.48	1.73	2.63%

*Units = ppbV; BIAS = MOD-OBS; NORM BIAS = (MOD-OBS)/OBS

The DV_{2023} at the nonattainment and maintenance monitors in the Midwest and Northeast U.S. from the three alternative comparisons: EPA vs LADCO, LADCO water vs no water, and LADCO bias filtered are presented in Section 5.

LADCO used the DVs_{2023} to identify nonattainment and maintenance sites in 2023 using the most recent 3-year monitored design values (2015-2017) per the CSAPR Update methodology (CSAPR Update, 2016). Under this methodology sites with an average DV_{2023} that exceed the 2015 NAAQS ($\geqq$ 71 ppb) and that are currently measuring nonattainment would be considered nonattainment receptors in 2023. Further, monitoring sites with a maximum DV_{2023} that exceeds the NAAQS would be considered a maintenance receptor in 2023. Under the CSAPR Update, maintenance only receptors include both those sites where the average DV_{2023} is below the NAAQS, but the maximum DV_{2023} is above the NAAQS; and monitoring sites with an average DV_{2023} above the NAAQS but with $DVs_{2009\text{-}2013}$ that are below the NAAQS.

The sites that LADCO identified through this process as having potential for nonattainment and maintenance designations for the 2015 O_3 NAAQS in 2023 were the focus of our source apportionment analyses. LADCO used the CAMx source apportionment APCA technique to assess the impacts of upwind sources on nonattainment and maintenance monitors in downwind states. Section 5.4 presents the results of the linkages of LADCO states to downwind maintenance and nonattainment monitors.

4 Ozone Source Apportionment Modeling

LADCO used the CAMx Anthropogenic Precursor Culpability Assessment (APCA) tool to calculate emissions tracers for identifying upwind sources of O_3 at downwind monitoring sites. We selected the APCA technique because it more appropriately associates O_3 formation to anthropogenic sources than the CAMx Ozone Source Apportionment Technique (OSAT). If any anthropogenic emissions are involved in a reaction that leads to O_3 formation, even if the reaction occurs with biogenic VOC or NOx, APCA tags the O_3 as anthropogenic in origin.

In the LADCO 2023 CAMx Source Apportionment modeling protocol (LADCO, 2018), we presented a configuration to tag both source regions and emissions inventory sectors for our APCA modeling. In the final APCA configuration, we primarily tagged only source regions in order to better leverage both the U.S. EPA 2023 EN CAMx modeling platform and to optimize the simulation on the LADCO computing cluster. We consolidated the 54 source tracers used by U.S. EPA into 32 tracers (Figure 9) based on an analysis of the linkages in the U.S. EPA modeling results. We maintained explicit O_3 tracers for only those states that had CSAPR linkages (at least 0.7 ppb MDA8) to nonattainment and maintenance monitors in the latest U.S. EPA 2023 modeling (US EPA, 2018). For the rest of the states, such as New England, most of the Southeast, and the West, we grouped them into single tracers for computational efficiency. Following from the U.S. EPA 2023 EN modeling platform, in addition to each source region, LADCO created explicit tags for fire emissions, biogenic emissions, offshore emissions, tribal emissions, Canada/Mexico emissions, and Initial/Boundary Conditions.

In a second CAMx APCA simulation, LADCO tagged emissions by inventory source sector to quantify how different types of emissions impact O_3 concentrations at key receptors. Table 5 lists the inventory sector tracers used by LADCO to track the contribution of emissions from the different sectors to O_3 concentrations in the modeling domain.

LADCO used the U.S. EPA 2023 EN data processing methods for preparing emissions for the APCA simulation. U.S. EPA developed a technique to convert all of the emissions data, including non-point sources such as biogenics and onroad mobile, to CAMx point source formatted data. Tagging of the emissions by state FIPs code is done during the emissions processing sequence to ensure that all of the emissions are properly attributed to the state from which they originate. This tagging is done to avoid the conventional problem in source apportionment modeling of mismatches between grid cell-based source regions and actual political boundaries. Additional details of the EPA emissions tagging approach are in U.S. EPA (2016).

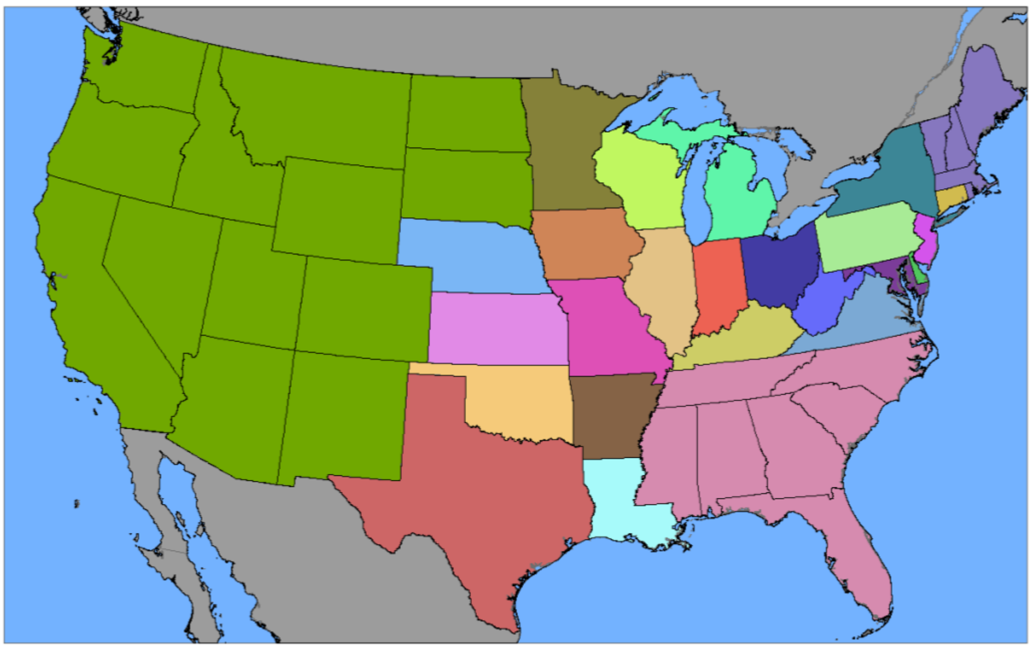

Figure 9. CAMx APCA Source Regions used by LADCO

Table 5. CAMx APCA inventory sector tracers

Tag #	Sector (Abbr)	Tag #	Sector (Abbr)
1	Biogenic (Biog)	9	Residential Wood Combustion (RWC)
2	Fugitive Dust (AFDust)	10	Onroad Mobile (Onroad)
3	Commercial Marine Vessels (CMV)	11	Offroad Mobile (Nonroad)
4	Point Fires (PtFire)	12	Nonpoint/Area (Nonpt)
5	Oil and Gas (OilGas)	13	Electricity Generating Point (EGU)
6	Agricultural (Ag)	14	Non-EGU Point (NEGUPt)
7	Agricultural Fire (AgFire)	15	Canada & Mexico (CanMex)
8	Rail (Rail)		

We used the CAMx APCA results to calculate an O_3 contribution metric for each potential nonattainment and maintenance monitor in the Midwest and Northeast U.S. (US EPA, 2016). The contribution metric is designed to provide a reasonable representation of the impacts of emissions from individual states and sources on the design values at downwind monitors in future years. In particular, per the CSAPR methodology, downwind monitors are considered to be linked to upwind sources if a modeled contribution assessment shows impacts at a monitor that equal or exceeds 1% of the NAAQS. For the 2015 O_3 NAAQS, source regions (and inventory sectors) that contribute 0.70 ppb or more to a monitor would be considered significant contributors to a nonattainment or maintenance monitor.

In Section 5 LADCO presents alternative design values and source apportionment modeling results for different transport modeling flexibilities. This section shows how the 2023 contributions and design values change with different EGU emissions, considerations of whether or not water cells are included in DV_{2023} calculations, and considerations of the model bias in the DV_{2023} calculations.

5 Results and Discussion

5.1 U.S. EPA 2011 EN Platform Benchmarking Results

LADCO simulated the entire O_3 season (May 1 – September 30, 2011) with CAMx using the U.S. EPA 2011 EN modeling platform. The purpose of the benchmarking simulation was to demonstrate that LADCO could closely reproduce the U.S. EPA results using the same model inputs and configuration used by U.S. EPA on a different computing infrastructure. By demonstrating that LADCO can reproduce the U.S. EPA results, we establish the validity of the U.S. EPA modeling platform on the LADCO systems and inherit the full model performance evaluation and vetting process used by U.S. EPA for the 2011 EN platform (US EPA, 2016).

Figure 10 and Figure 11 compare O_3 season MDA8 O_3 between the LADCO 2011 (LADCO_2011en) and the U.S. EPA 2011 EN (EPA_2011en) simulations at the locations of all of the U.S. EPA AQS and Clean Air Status Trends Network (CASTNet) monitors in the CONUS12 domain, respectively. The data for these figures are paired in space and time, meaning that each symbol on the plot represents a comparison of the two simulations at the same monitor on the same day. Although there is some variability between the two runs (AQS maximum absolute difference is 7.06 ppbV), the runs are not expected to be exactly the same due to numerical differences that arises from the different computing architectures used for the U.S. EPA and LADCO simulations. For 194,953 AQS data pairs, the Pearson correlation coefficient for the LADCO and U.S. EPA simulations is 0.99969 and the coefficient of determination (R^2) is 0.999, indicating that the two simulations produced very similar results. The comparison of predicted O_3 concentrations at the rural CASTNet monitors shows similar correspondence between the runs (R^2 = 0.999). The LADCO simulation had a small negative mean bias (MB) relative to U.S. EPA across both the AQS (MB: -0.29 ppb) and CASTNet (MB: -0.2 pbb) networks, indicating that, on average, the LADCO 2011 simulation estimated slightly lower ozone than the U.S. EPA 2011 simulation.

Figure 12 shows a timeseries comparison of MDA8 O_3 for the EPA and LADCO 2011 simulations at a single monitor location. Each data point on this figure represents the daily

MDA8 for the two simulations at the Chiwaukee Prairie monitor in southeastern Wisconsin. This figure also shows a very close correspondence between the EPA (blue line) and LADCO (red line) simulations relative to the observations (black line).

The close correspondence in predicted O_3 between the U.S. EPA and LADCO 2011 simulations illustrated in these figures is consistent across states, monitoring networks and time periods. These results demonstrate the LADCO was able to effectively port the U.S. EPA 2011 EN modeling platform to the LADCO computing cluster and use the platform as the basis for projecting future year O_3 concentrations. Despite the numerical differences introduced into the 2011 EN simulation by the LADCO computing architecture, LADCO will forecast 2023 O_3 on the same computing architecture as the 2011 benchmark simulation to ensure comparability between the LADCO 2011 and 2023 simulations. Using a common computing platform and applying the RRF approach for forecasting design values will ensure that LADCO's future year O_3 estimates are not contaminated by numerical differences due to the computing architecture.

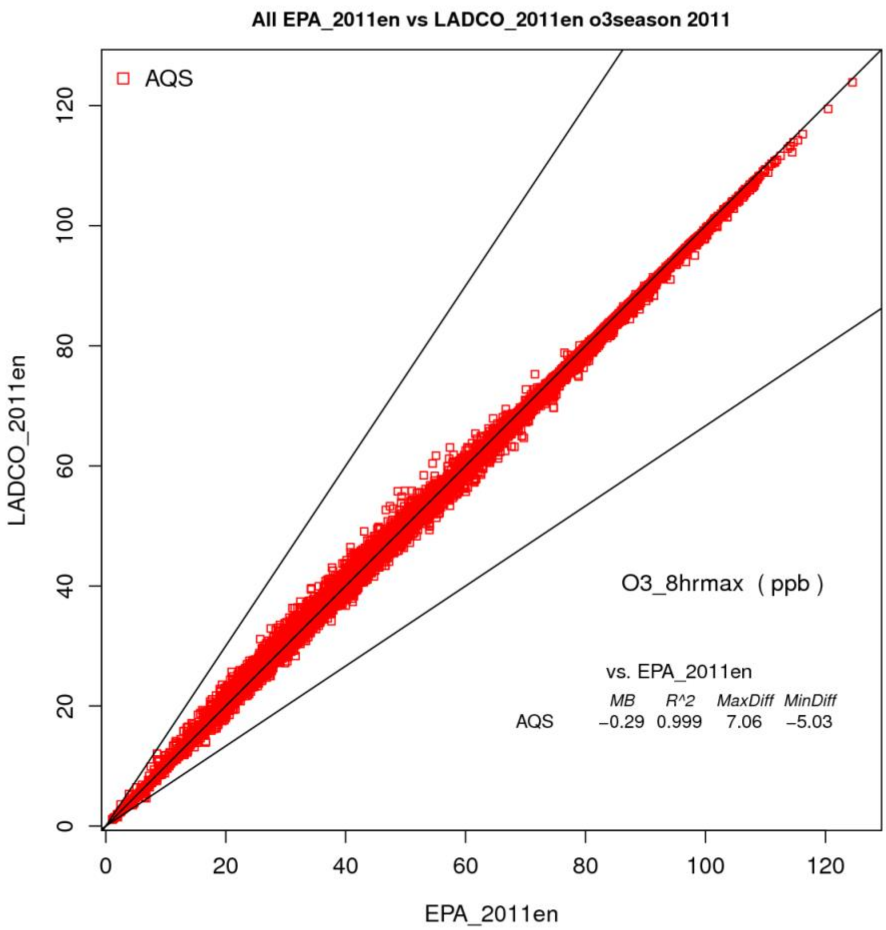

Figure 10. LADCO vs EPA 2011 EN summer season AQS MDA8 O_3

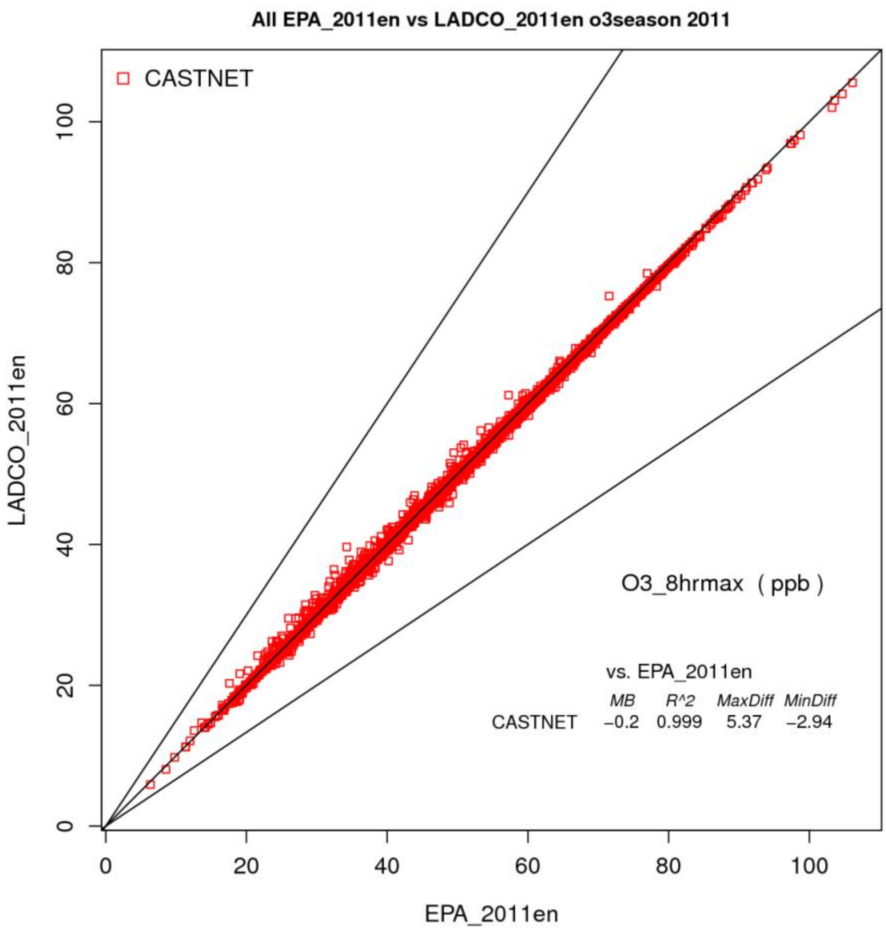

Figure 11. LADCO vs EPA 2011 EN summer season CASTNet MDA8 O_3

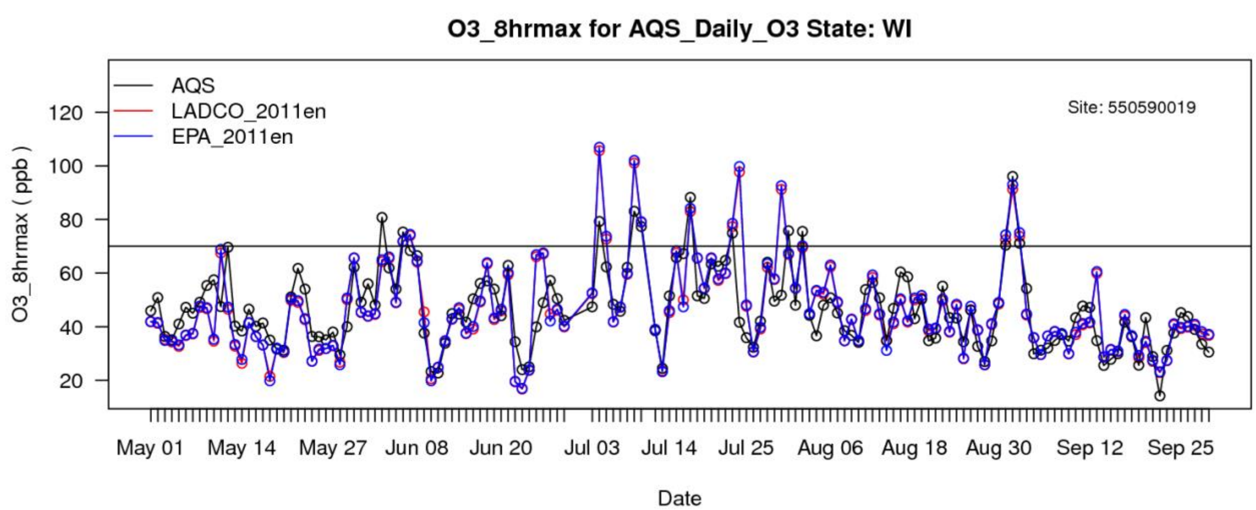

Figure 12. Timeseries of MDA8 O_3 at Chiwaukee Prairie, WI comparing EPA and LADCO 2011 simulations.

5.2 CAMx Model Performance Discussion

U.S. EPA (2016) reported model performance for the 2011 CAMx modeling platform used here. As LADCO demonstrated our ability to reproduce the U.S. EPA simulation with only small variations in the results, the conclusions reached by U.S. EPA from the operational model performance evaluation (MPE) of this simulation apply to the modeling platform used by LADCO for projecting design values and evaluating interstate O_3 transport. The U.S. EPA (2016) MPE results are summarized here.

The U.S. EPA MPE focused on the skill of CAMx at simulating high MDA8 concentrations (≧60 ppb). U.S. EPA evaluated the model by comparing CAMx-predicted MDA8 to observations at the U.S. EPA AQS and CASTNet networks. Statistical evaluations were performed by U.S. EPA using modeled and observed data that were paired in space and time. Statistics were developed across spatial and temporal scales, for individual monitoring sites, and in aggregate across multiple sites by state and region.

U.S. EPA (2016) stated that the performance of the 2011 "EL" platform, which was also used as the basis for the 2023 "EN" air quality projections, are within the range of other recent peer-reviewed and regulatory applications. For the regions of concern for the LADCO states, CAMx on average tends to overestimate summer season (May – September) MDA8 at AQS sites on high O_3 days in the Northeast (Mean Bias (MB) = 1.2 ppb) and underestimate MDA8 at AQS sites in the Ohio Valley (MB = -0.6 ppb) and the Upper Midwest (MB = -4.0 ppb) with mean errors (ME) in all three regions around 7.5 ppb; see U.S. EPA (2016) Table A-1. Figure 13 illustrates the spatial variability in model performance on high O_3 days. Mean bias is within +/- 5 ppb at many sites in the Midwest and Northeast, with some over-prediction of 5-10 ppb at sites in the Northeast. The model also under-predicted by 5-10 ppb sites in the LADCO region, particularly some of the coastal WI monitors.

Investigation of the diurnal variability at key monitors demonstrated that CAMx generally captured day to day fluctuations in observed MDA8 but missed the peaks on many of the highest observed days. Figure 14 through Figure 16 compare daily AQS observations of MDA8 to the U.S. EPA and LADCO 2011 CAMx simulations at a few Lake Michigan shoreline monitors in Michigan (MI) and Wisconsin (WI). At the Allegan County, MI monitor (Figure 14), CAMx tended to underestimate the high observed days (MB = -0.4 ppb). CAMx also underestimated the high observed O_3 days at the Wayne County, MI monitor (Figure 15; MB = -10.8 ppb) and the Sheboygan County, WI monitor (Figure 16; MB = -8.4 ppb). Despite deficiencies in model performance on days when the observed MDA8 $O_3 \geqq 60$ ppb, the statistics in Table 6 show that CAMx performance was still within acceptable model performance criteria at all of the sites reported here (EPA, 2014b). Timeseries plots comparing the LADCO 2011, EPA 2011, and observations for the rest of the high O_3 monitors listed in Table 6 are provided in the Appendix of this TSD (Figure 54 through Figure 62).

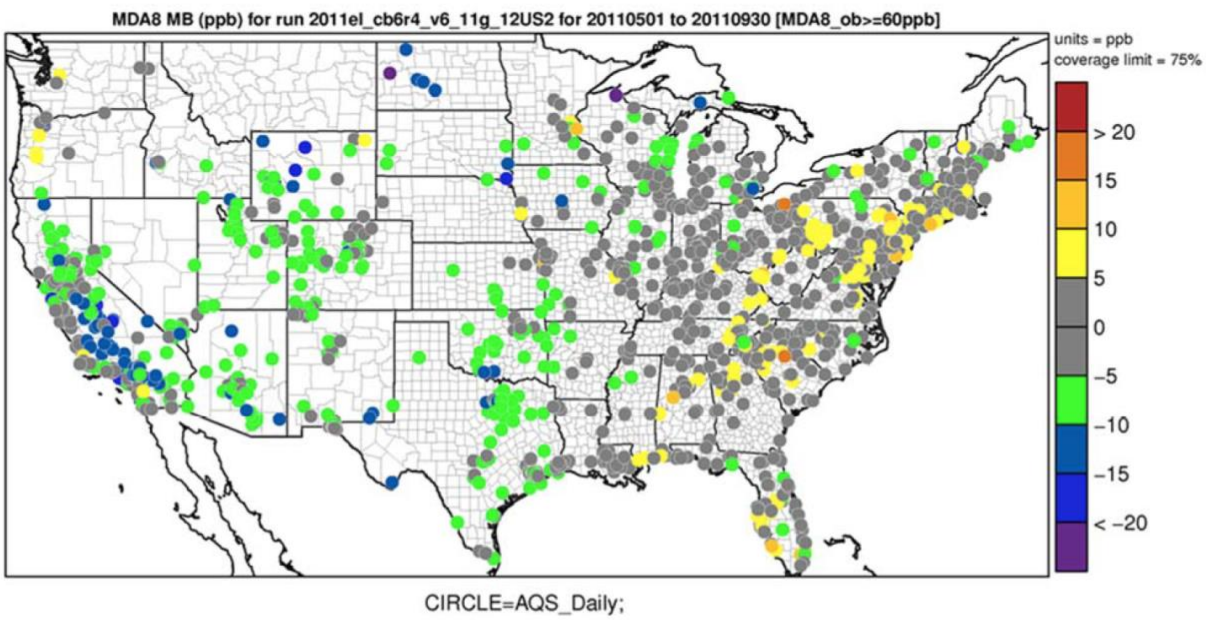

Figure 13. Mean Bias (ppb) of summer season MDA8 O_3 >= 60 ppb (US EPA, 2016).

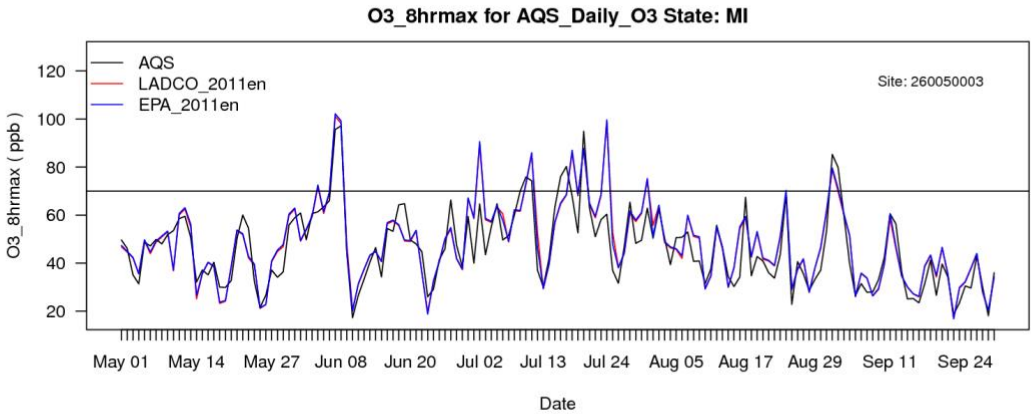

Figure 14. Timeseries of observed AQS, LADCO modeled, and EPA modeled summer season MDA8 O_3 at site 260050003 in Allegan County, MI

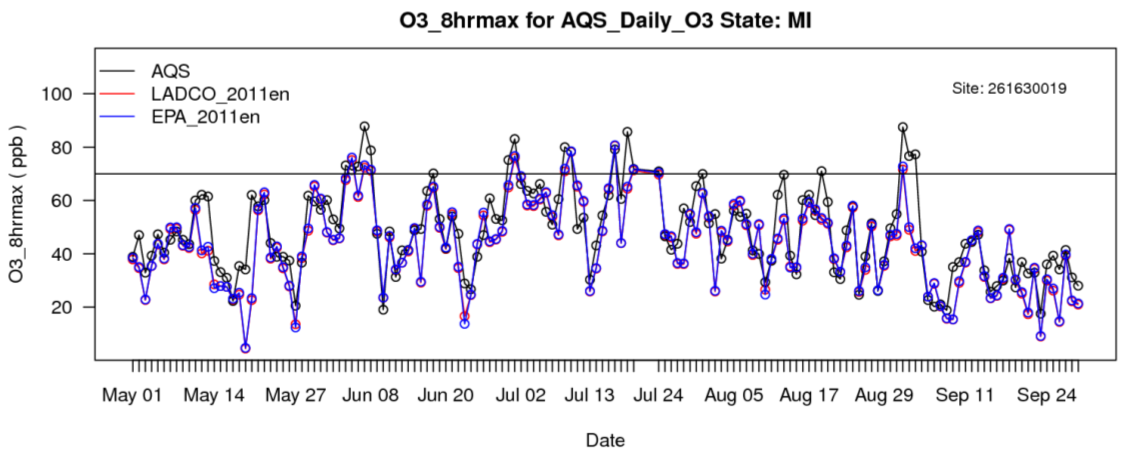

Figure 15. Timeseries of observed AQS, LADCO modeled, and EPA modeled summer season MDA8 O_3 at site 261630019 in Wayne County, MI

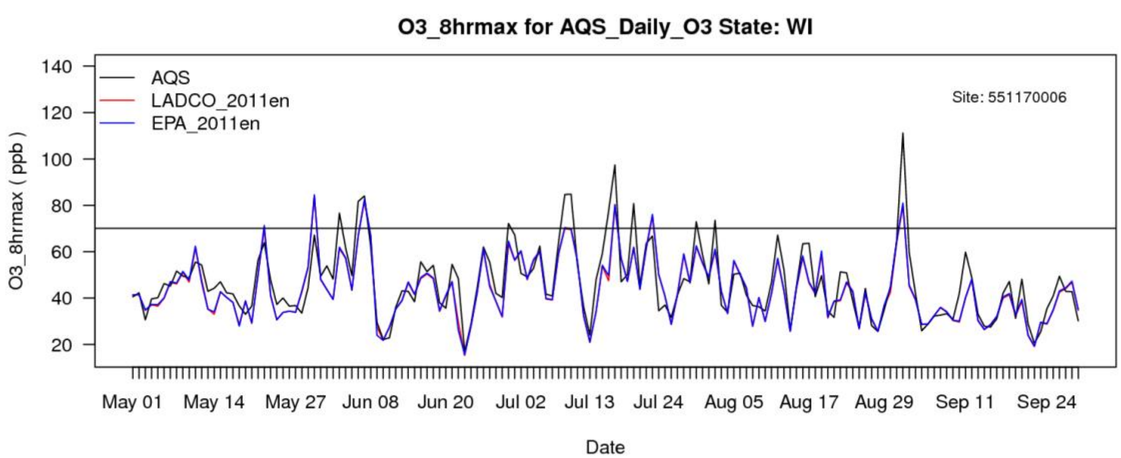

Figure 16. Timeseries of observed AQS, LADCO modeled, and EPA modeled summer season MDA8 O_3 at site 551170006 in Sheboygan County, WI.

Table 6. LADCO CAMx May – September 2011 MDA8 O_3 model performance statistics at key monitors where observations >= 60 ppb

Site_ID	County, ST	Mean Obs	Mean Mod	MB (ppb)	ME (ppb)	NMB (%)	NME (%)
90010017	Fairfield, CT	69.6	68.6	-1.0	12.5	-1.5	18.0
90013007	Fairfield, CT	73.0	73.4	0.5	9.6	0.7	13.2
90019003	Fairfield, CT	72.0	73.5	1.5	9.0	2.1	12.5
90093002*	New Haven, CT	74.3	76.9	2.6	8.7	3.5	11.8
240251001	Harford, MD	73.7	73.6	0.0	8.7	-0.1	11.8
260050003	Allegan, MI	69.3	68.9	-0.4	8.2	-0.6	11.8
261630019	Wayne, MI	69.3	58.6	-10.8	11.4	-15.5	16.4
360810124	Queens, NY	72.1	65.1	-7.1	9.9	-9.8	13.7
360850067	Richmond, NY	71.3	67.6	-3.7	8.7	-5.1	12.1
361030002	Suffolk, NY	73.0	70.0	-3.0	7.4	-4.2	10.2
550790085	Milwaukee, WI	71.1	63.8	-7.4	11.0	-10.4	15.5
551170006	Sheboygan, WI	72.9	64.5	-8.4	11.2	-11.5	15.3

* The New Haven County, CT site 90093002 shut down in 2012 and was replaced by site 90099002; both monitors were sited at the same location.

5.3 LADCO 2023 Air Quality Projections

LADCO modified the emissions in the U.S. EPA 2023 EN platform to create a LADCO 2023 modeling platform (see Section 2.5). The LADCO 2023 simulation forecasted air quality for the continental U.S. using the best available information for North American emissions, including EGU emissions forecasts from the ERTAC v2.7 model. Figure 17 shows the O_3 season (May through September) maximum of MDA8 O_3 for the LADCO and U.S. EPA 2023 CAMx simulations in the CONUS12 modeling domain. Figure 18 shows the difference in O_3 season maximum (LADCO – EPA) between the two simulations. Cool colors indicate that the U.S. EPA simulation forecasted higher O_3 than the LADCO simulation; warm colors indicate higher O_3 in the LADCO forecast. In general, the U.S. EPA simulation predicted higher O_3 in the Midwest, Northeast, Gulf Coast, and Pacific Coast states; the LADCO simulation predicted higher O_3 in the Four Corners region and Central Arkansas. Note that the trends shown in these figures mask finer temporal resolution features (i.e., hourly and daily) that also exist between the LADCO and U.S. EPA 2023 simulations.

Figure 19 and Figure 20 compare O_3 season MDA8 O_3 between the LADCO 2023 (LADCO_2023en) and the LADCO 2011 (LADCO_2011en) simulations at the locations of all of the AQS and CASTNet monitors in the CONUS12 domain, respectively. As both of these simulations were run on the LADCO computing cluster, the differences in the runs are due entirely to the emissions projections from 2011 to 2023. The LADCO simulation predicted that MDA8 O_3 will decrease in 2023 relative to the base year by an average of 5.07 ppbV nationally across all AQS monitors and by an average of 5.95 ppbV across all CASTNet monitors. These changes are similar to the U.S. EPA forecasts, which estimated average decreases in MDA8 O_3 of 5.23 ppbV at the AQS monitors and 6.15 ppbV at the CASTNet monitors.

Figure 22 and Figure 23 show the O_3 DV_{2023} and RRFs from the LADCO 2023 simulation, respectively. LADCO generated these results with SMAT-CE using the standard U.S. EPA attainment test configuration (top 10 modeled days, 3x3 cell matrix around the monitor, including water cells). Note that these results are not filtered for model biases. The bias filtered attainment test results are presented in Section 0. The LADCO O_3 DVs_{2023} presented here also differ from the U.S. EPA calculations because we used observational data completeness criteria based on the 2015 O_3 NAAQS. U.S. EPA noted (LADCO email correspondence with Brian Timin, US EPA OAQPS, 2018) that for consistency with their 2008 O_3 NAAQS Transport modeling TSD (US EPA, 2015) they chose to use completeness criteria for the monitoring data based on the 2008 O_3 standard, even when presenting results for the 2015 form of the standard. The completeness criteria are tied to the level of the standard in cases in which the number of valid observations falls below a statutory threshold but when at least one of the valid observations is greater than the NAAQS (see 40 CFR Part 50 Appendix U). By using the 2015 O_3 NAAQS for determining completeness, LADCO includes more available data points in the DV calculations than U.S. EPA because the lower standard is more inclusive of the available monitoring data (i.e., there are more MDA8 O_3 observations >= 70 ppb than there are observations >= 75 ppb).

The LADCO 2023 CAMx simulation predicted that no monitors in the Midwest and three monitors in the Northeast will be nonattainment (orange) for the 2015 O_3 NAAQS. The highest mean DV_{2023} in these regions is the Babylon monitor in Suffolk County, NY (AIRS ID: 36103002) monitor at 71.6 ppbV; the highest maximum DV_{2023} is the Westport monitor in Fairfield, CT (AIRS ID: 90019003) at 74.2 ppbV. The RRF plot indicates that the largest reductions (25-30%) in DVs_{2023} are forecasted to occur in Chicago, Cleveland, and North Carolina. Regionally, the Mid-Atlantic and Northeast are forecasted to experience widespread reductions in O_3 DVs_{2023} in the range of 20-25%.

Figure 23 shows the LADCO DVs_{2023} zoomed in on the Lake Michigan region. This plot highlights that all monitors in the region are forecast to be in attainment of the 2015 O_3 NAAQS in 2023. Four LADCO region monitors, Kohler Andrae in Sheboygan Co., WI (70.5 ppb), Holland, MI (68.8 ppb), Berrian Co., MI (67.0), and 7 Mile in Detroi., MI (68.8 ppb) were forecast to be within 5% of not attaining the 2015 O_3 NAAQS. The Bayside monitor in Milwaukee Co., WI (63.6) was forecast to be within 10% of nonattainment status.

Table 7 presents the average and maximum DVs_{2023} for the near nonattainment and maintenance monitors in the Midwest and Northeast. The red highlighted values indicate forecasted maintenance status for the 2015 O_3 NAAQS. ***There are no monitors in the LADCO region that are forecast to be nonattainment in 2023. The Kohler Andrae monitor in Sheboygan, WI (AIRS ID: 551170006) and the Holland, MI monitor (AIRS ID: 260050003) are the only forecasted maintenance monitors in the LADCO region***.

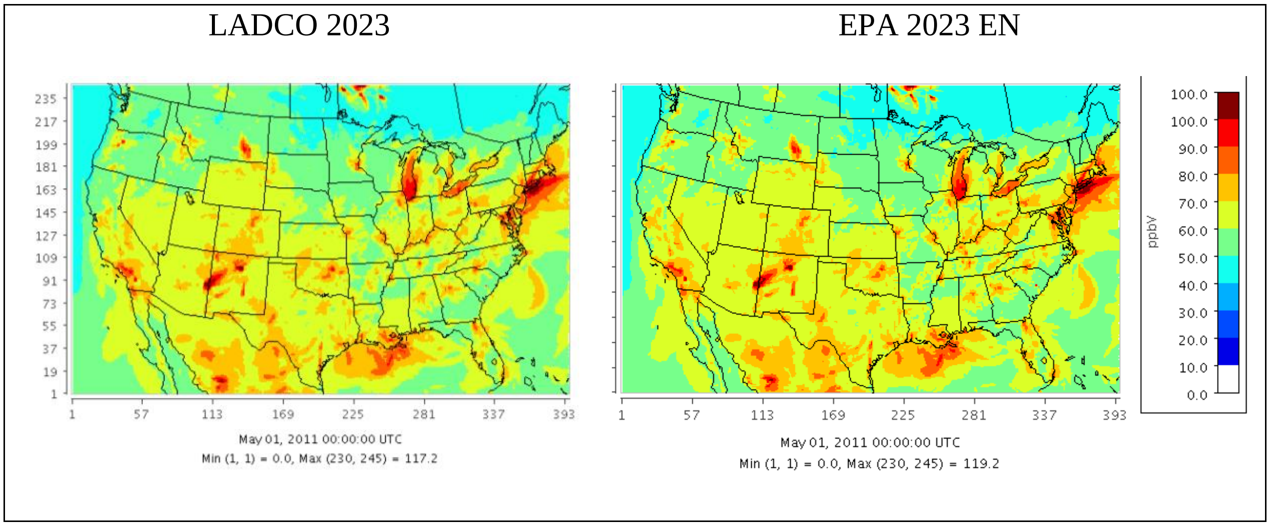

Figure 17. LADCO and EPA CAMx May - Sept maximum 2023 MDA8 O_3

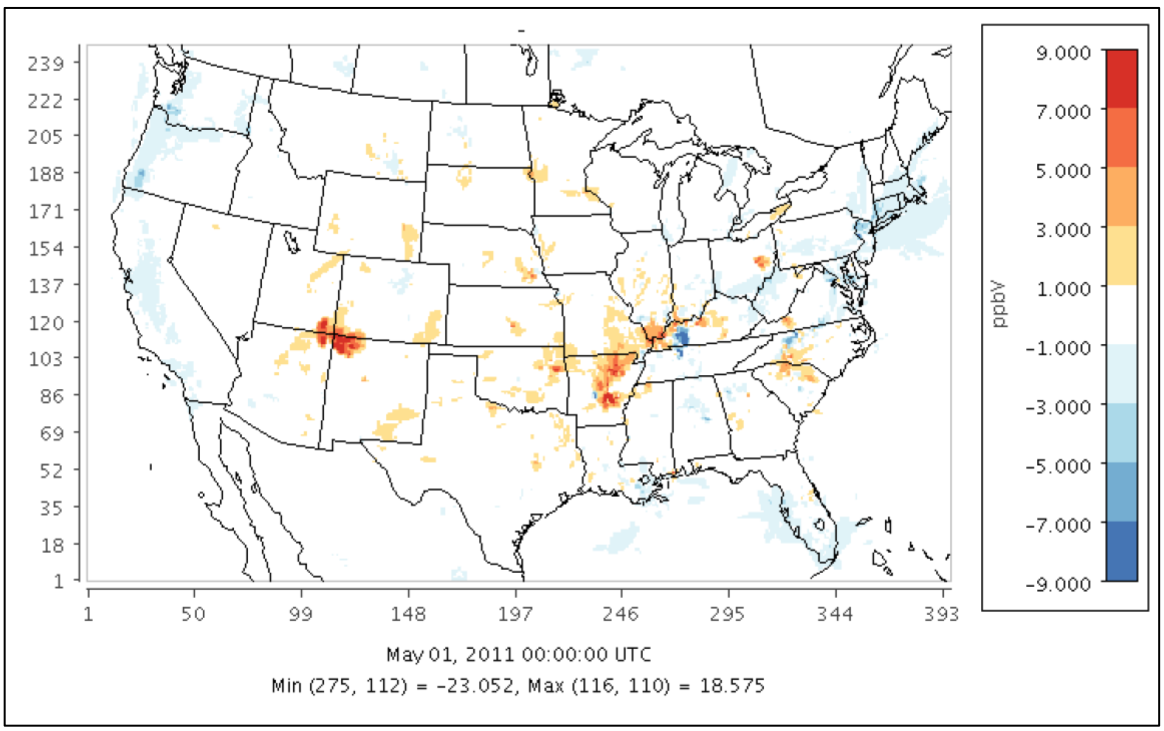

Figure 18. CAMx May - Sept difference (LADCO-EPA) in maximum 2023 MDA8 O_3

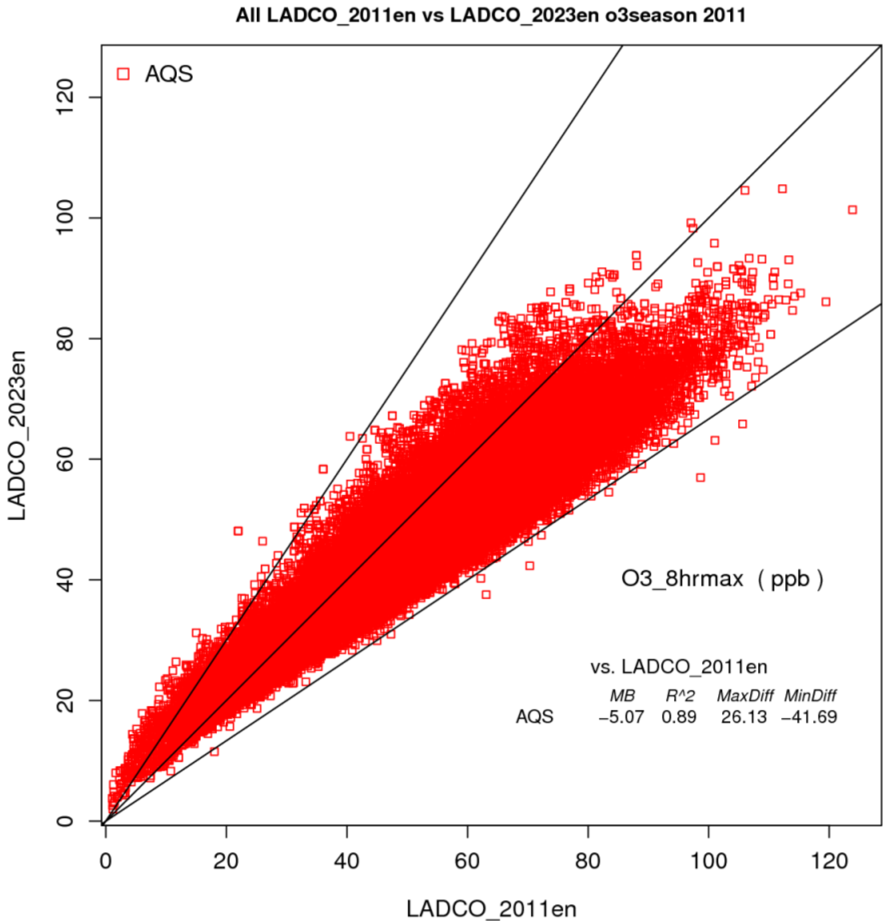

Figure 19. LADCO 2023 vs 2011 summer season AQS MDA8 O_3

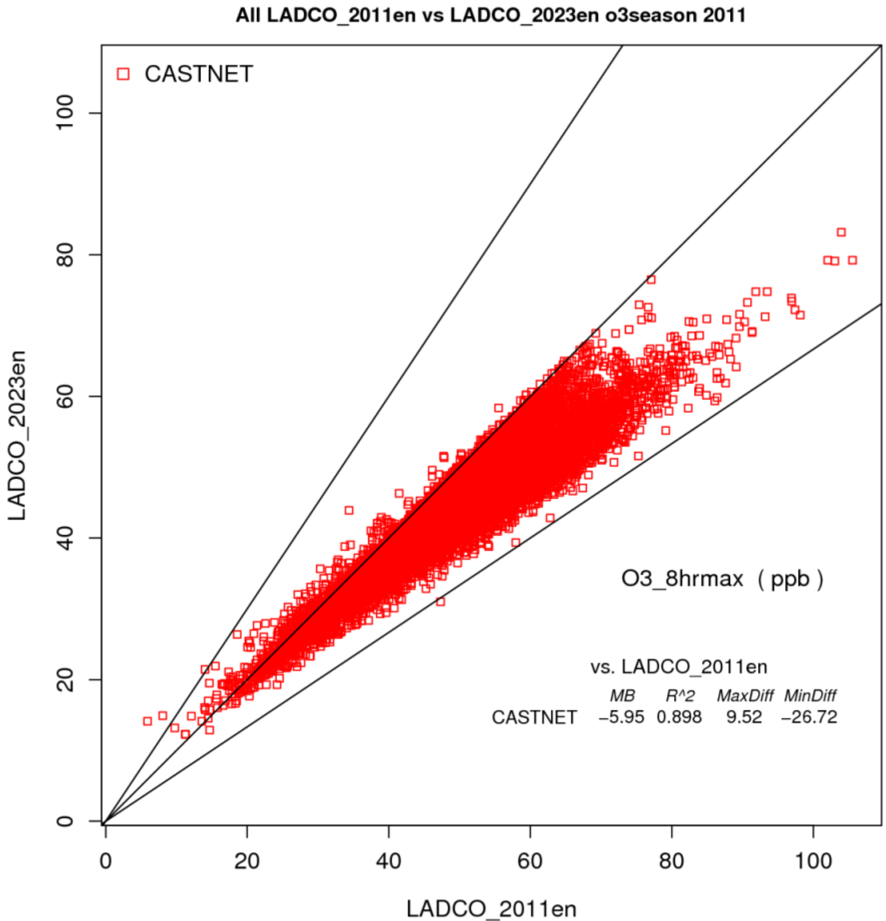

Figure 20. LADCO 2023 vs 2011 summer season CASTNET MDA8 O_3

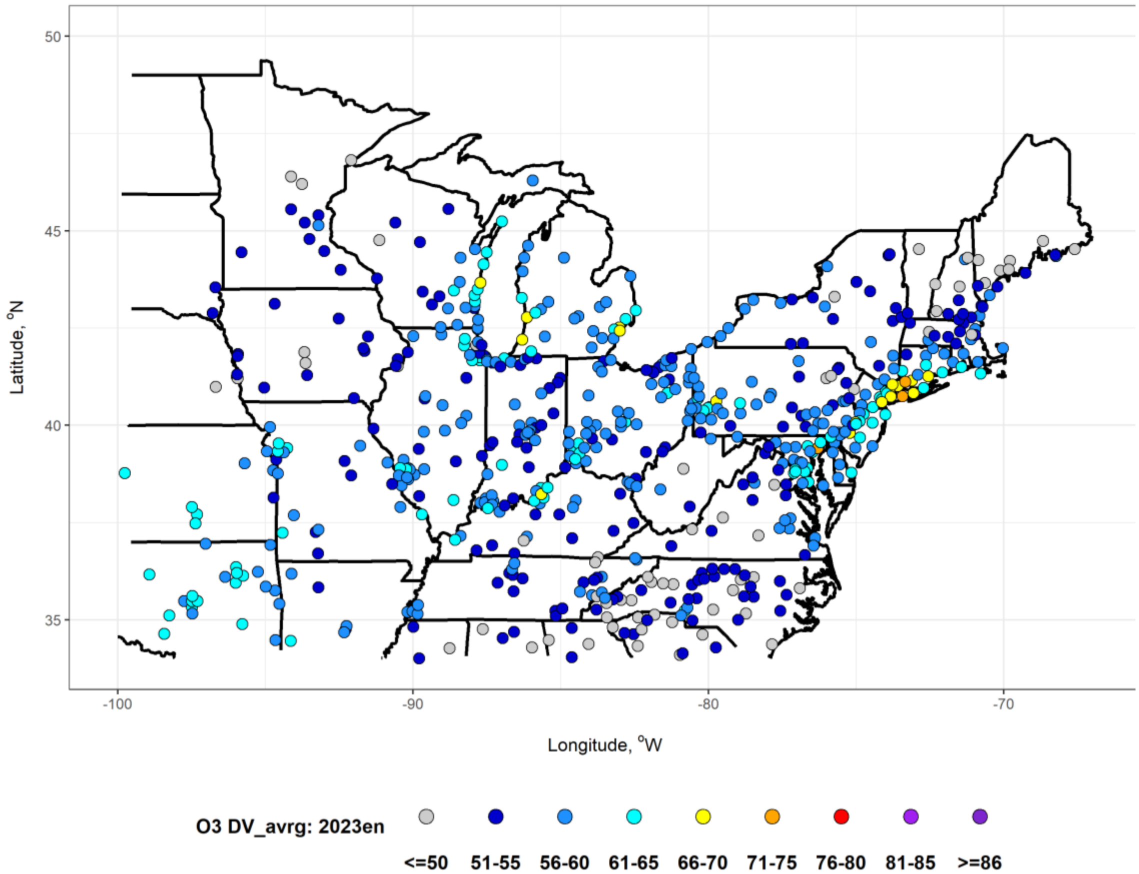

Figure 21. Future year O_3 design values calculated with WATER from the LADCO 2023 CAMx simulation.

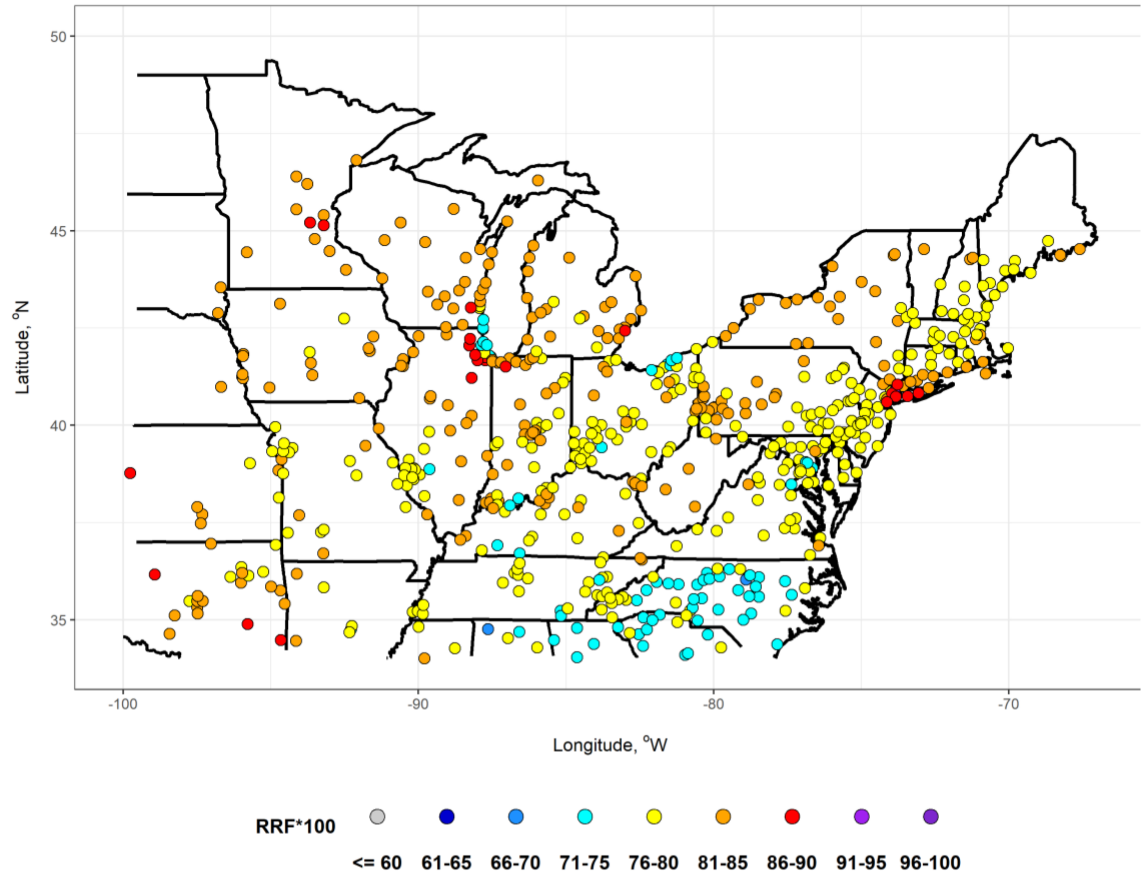

Figure 22. Future year O_3 relative response factors calculated with WATER from the LADCO 2023 CAMx simulation.

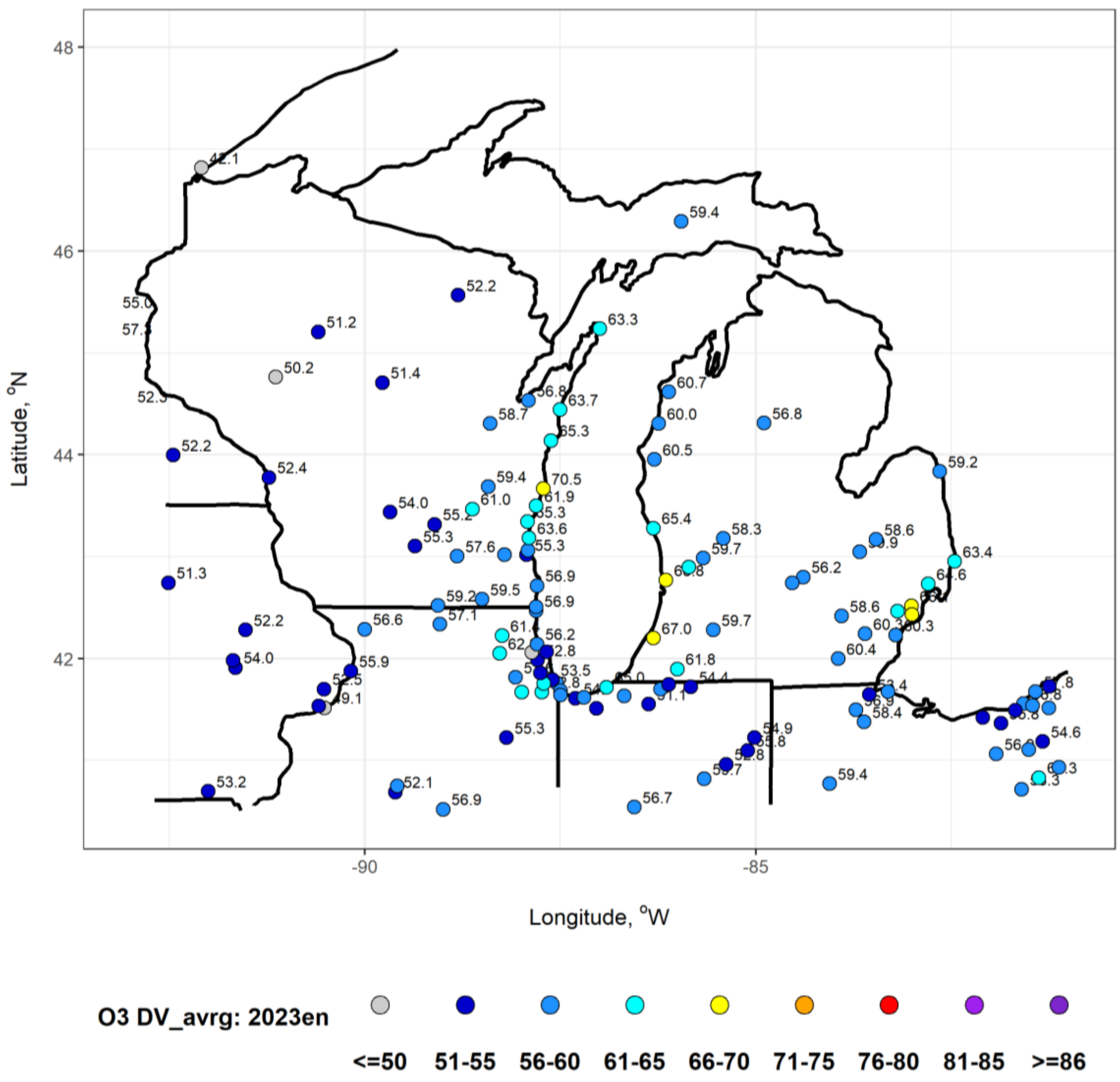

Figure 23. Future year O_3 design values calculated with WATER from the LADCO 2023 CAMx simulation; Lake Michigan zoom.

Table 7. LADCO 2023 O_3 design values with WATER at nonattainment and maintenance monitors in the Midwest and Northeast

AQS ID	Monitor ID	ST	LADCO 2023		2009-2013		2015-2017 DV
			3x3 avrg	3x3 max	3x3 avrg	3x3 max	
361030002	Babylon	NY	71.6	73.1	83.3	85.0	76.0
90019003	Westport	CT	71.4	74.2	83.7	87.0	83.0
240251001	Edgewood	MD	71.0	73.3	90.0	93.0	75.0
360850067	Richmond	NY	70.9	72.4	84.3	87.0	76.0
551170006	Sheboygan Kohler Andrae	WI	70.5	72.8	81.3	83.0	80.0
90093002*	New Haven	CT	69.9	72.6	85.7	89.0	82.0
90013007	Stratford	CT	69.8	73.7	84.3	89.0	83.0
360810124	Queens	NY	69.2	71.0	78.7	81.0	74.0
90010017	Greenwich	CT	68.9	71.2	70.0	71.0	79.0
260050003	Holland	MI	68.8	71.5	78.0	80.0	73.0
261630019	Detroit 7 Mile	MI	68.3	70.3	80.3	83.0	73.0
550790085	Milwaukee Bayside	WI	63.6	66.6	78.3	82.0	71.0

* The New Haven County, CT site 90093002 shut down in 2012 and was replaced by site 90099002; both monitors were sited at the same location.

5.4 Interstate Transport Linkages

Table 8 shows the MDA8 O_3 DV_{2023} CSAPR linkages between states and monitors estimated by the LADCO 2023 simulation. These linkages are derived from the relative contribution factor (RCF) approach presented in U.S. EPA (2016) and are based on attainment test calculations that include water cells and do not include any filtering for model biases. The linkages in Table 8 are provided for the same monitors highlighted in Table 7. The three nonattainment monitors in the LADCO 2023 simulation are highlighted with purple text; the maintenance monitors are highlighted with red text. The states with contributions that equal or exceed 1% of the 2015 O_3 NAAQS (0.70 ppbV) are highlighted with yellow shading; contributions that exceed 1 ppb are highlighted with orange.

As described above, the two monitors in the LADCO region projected by the LADCO 2023 modeling to be in maintenance for the 2015 O_3 NAAQS are the Kohler Andrae monitor in

Sheboygan, WI with a maximum DV_{2023} of 72.8 ppbV and the Holland, MI monitor with a maximum DV_{2023} of 71.5 ppbV. Illinois is the highest contributing source region linked to the Sheboygan, WI monitor (14.93 ppbV) followed by WI (9.10 ppbV), IN (6.19 ppbV), MI (1.85 ppbV), and TX (1.76 ppbV). Illinois is the highest contributing source region linked to the Holland, MI monitor as well (19.25 ppbV), followed by IN (6.91 ppbV), MI (3.35 ppV), MS (2.59 ppbV), and TX (2.40 ppbV). While all of the LADCO states, with the exception of MN and WI, have CSAPR-significant linkages to the maintenance monitors in the Northeast, OH has the largest single contribution to a monitor outside of the LADCO region (2.83 ppbV at Edgewood, MD). The 7 Mile monitor in Detroit., MI experiences the largest influence from outside of the U.S. (CNMX = 3.14 ppbV) of all of the monitors in Table 8.

Figure 24 presents these results in a stacked bar form. Only the source regions with contributions >= 0.7 ppbV are explicitly shown in this figure. All of the source regions with contributions less than this amount are grouped into the "others" category. A few contribution trends that are highlighted in this plot include:

- The home state is a significant single contributor to ozone at each monitor
- IL and IN are the largest upwind contributors to ozone at the Lake Michigan shoreline monitors
- PA, NY, and NJ are the largest upwind contributors to ozone at the Northeast monitors
- Offshore sources (commercial marine) have more of an impact on ozone at the monitors in the Northeast than in the Great Lakes region
- Canada/Mexico sources have the largest impact on ozone at the Detroit, MI monitor of all of the monitors shown in the figure

Figure 25 through Figure 33 show the 2023 ozone season maximum of the CAMx APCA O_3 tracers for the LADCO states, Texas, Offshore (commercial marine) sources, and Canada+Mexico. While these plots do not indicate the conditions in which these maximum values occur (i.e., on high or low O_3 days), they do show the maximum magnitudes and spatial extents of the influence of each state on regional O_3 concentrations. Figure 25 shows that CAMx estimated that IL contributes a domain maximum O_3 concentration of 72 ppbV. The maximum influence of IL emissions on O_3 is near Chicago and over Lake Michigan. Within the LADCO region, IL sources have the greatest influence on O_3

concentrations in southeast WI, northwest IN, and the Lower Peninsula of MI. CAMx estimated that IL contributes a maximum of 2-4 ppbV O_3 to the coastal areas in the Northeast and up to 8 ppbV O_3 as far south as the Louisiana Gulf Coast.

Figure 26 shows that CAMx estimated that IN contributes a domain maximum 47 ppbV O_3. The highest contributed O_3 concentrations from IN sources are in southern Lake Michigan. Within the LADCO region, IN sources have the greatest influence on O_3 concentrations in southern IL, southern MI, and central OH. CAMx estimated similar O_3 impacts for IN as for IL in the coastal areas in the Northeast and in the Gulf Coast.

The CAMx estimates for MI O_3 tracers in Figure 27 show a domain maximum contribution of 42 ppbV with the greatest impacts over Lakes Michigan, Ontario, and Erie. Within the LADCO states, MI sources have the greatest influence on O_3 concentrations in northern IN and OH. MI is also estimated to have a slightly greater impact on O_3 in the Northeast than both IL and IN, with maximum O_3 tracer concentrations of 4-6 ppbV extending off the Northeast coast.

Figure 28 shows that the maximum O_3 impact from MN sources is estimated to be 51 ppbV and occurs around the Twin Cities. MN has the greatest regional influence on O_3 concentrations in northern WI. The MN O_3 tracers are estimated to extend as far south as Dallas and east into central PA.

Figure 29 shows that OH sources have the greatest impact on O_3 over Lake Erie with a domain maximum tracer concentration of 72 ppbV. Within the LADCO region, OH sources are estimated to have the greatest impact on O_3 in eastern IN and southeastern MI. As the easternmost LADCO state, OH is estimated to have the greatest impact on O_3 in the Northeast, with maximum OH tracer concentrations of 8-10 ppbV extending to the Northeast

As shown in Figure 30, WI sources are estimated by CAMx to have the greatest impact on O_3 concentrations along the WI shoreline of Lake Michigan. The highest WI O_3 tracer concentration of 42 ppbV occurs over Lake Michigan off the southeast coast of the state. Within the region, WI sources have the greatest influence on O_3 concentrations in western MI and the far northeast corner of IL. CAMx estimates that WI sources influence O_3

concentrations as far away as northeast TX and along the Northeast U.S. coast by a maximum range of 2-4 ppbV.

Figure 31 shows that TX sources are estimated to impact O_3 concentrations in all of the LADCO states. The maximum influence from TX sources on O_3 in the LADCO region are estimated by CAMx to be in southern IL and southern WI in the range of 8-10 ppbV. While the O_3 tracer from offshore sources shown in Figure 32 demonstrates relatively small impacts on O_3 in the LADCO states (< 4 ppb), it does indicate that this source has a notable impact on O_3 along the coast of the Mid-Atlantic and Northeast states (~10-20 ppb). Figure 33 shows that sources in Canada and Mexico are estimated by CAMx to influence O_3 concentrations through most of the Continental U.S. The largest influence in the LADCO region is near the Canadian border in eastern MI. Canadian emissions are estimated to impact most of the LADCO states by a seasonal maximum of 2-10 ppbV.

Table 9 and Figure 34 through Figure 44 present the results from a second 2023 CAMx APCA simulation in which LADCO tagged inventory sectors instead of source regions for tracking ozone contribution impacts. We designed this simulation to demonstrate how the different inventory sectors may influence ozone across the modeling domain and at the problem monitors. The inventory sectors that we tagged in this simulation include:

- Commercial Marine Vessels – class 1, 2, and 3 near-shore and off-shore commercial vessels; includes emissions from hoteling, maneuvering, and cruising operating modes
- Fires – point wildfires
- Oil & Gas – point and nonpoint upstream oil and gas sources
- Agriculture – livestock, crop, and orchard operations; includes emissions from fertilizer application, farming equipment, confined animal feeding operations, manure management, and heaters
- Fugitive Dust – construction, agricultural, mining equipment dust
- Agricultural Fires – crop field burning
- Rail – class 1, 2, and 3 on-rail sources; rail yards included in non-EGU point
- Residential Wood Combustion – heating and recreational wood burning appliances and firepits
- Onroad Mobile – MOVES on-road mobile; includes heavy duty diesel hotelling
- Nonroad Mobile – NONROAD/MOVES off-road mobile; includes lawn/garden, construction, mining, recreational, and recreational marine sources

- Area/Nonpoint – commercial, industrial, residential area sources; includes solvents, surface coating, consumer products, refueling/portable fuel canisters, midstream oil & gas
- Electricity Generating Units (EGU) Point – point inventory of thermal power generation sources
- Non-Electricity Generating Unit Point – point inventory of industrial, commercial, institutional sources that do not generate power; includes manufacturing, downstream oil & gas, airports, landfills, maritime ports
- Canada/Mexico – all non-US area and point sources in North America
- Initial/Boundary Conditions – ozone and ozone precursors entering the modeling domain from the horizontal and top boundary
- Biogenic – vegetation volatile organic compounds (VOCs) and soil NO emissions; includes trees, shrubs, and crops

Table 9 and Figure 34 show that onroad and nonroad mobile were estimated to be the largest inventory sector contributors to ozone at the high O_3 monitors. Onroad mobile was forecast to contribute 9.8 to 12.9 ppbV MDA8 O_3 at all of the high O_3 monitors. It is followed in the contribution ranking by nonroad mobile, which was forecast to contribute O_3 concentrations at these monitors in the range of 9.3 to 13.6 ppbV. EGU and non-EGU point sources were estimated to be the next largest inventory sectors contributing to O_3 at these monitors with tracer concentrations in the range of 3.8 to 8.9 ppbV. While commercial marine vessels (CMV) were estimated to have fairly large impacts on O_3 concentrations at the Atlantic coast monitors (maximum contribution at New Haven, CT = 5.9 ppbV), their maximum impact in the LADCO region is at Sheboygan, WI (1.0 ppbV). Upstream oil and gas sources were forecast to have a fairly consistent contribution across all of the high O_3 monitors, with the highest tracer concentration occurring at Allegan, MI (2.9 ppbV). Nonpoint/area sources were forecast to be significant at all of these monitors, and may be a larger contributor than EGU or non-EGU point sources to O_3 at many of the CT and NY monitors.

Figure 35 to Figure 44 show the O_3 season maximum concentrations for each of the inventory sector tracers in LADCO's 2023 CAMx APCA simulation. These plots illustrate the maximum spatial extent and major areas of influence of the emissions from the different inventory sectors. A summary of these plots follows.

- Nonpoint/Area (Figure 35) sources were forecast to have the largest impact in and near population centers. Eastern New York/New Jersey is the region of the country with the largest impact of this sector on O_3 concentrations.
- Oil and Gas (Figure 36) sources were forecast to impact most of the country outside of California and the Pacific Northwest. The areas of largest influence are near the major oil and shale plays in Texas, Oklahoma, the Intermountain West, and the Marcellus Shale region.
- Commercial Marine Vessels (Figure 37) were forecast to impact the near coast sites, particularly in the Gulf Coast of Texas and Louisiana, southeastern Florida, and along the Mid-Atlantic and Northeast.
- Rail (Figure 38) sources were predicted to have modest (2-4 ppbV) impacts on O_3 across most of the country, with the largest impacts (8-10 ppbV) occurring in the Great Plains.
- Onroad Mobile (Figure 39) sources were predicted to impact O_3 concentrations across all of the country in the range of 4-8 ppb with larger impacts (14-20+ ppb) in and near urban areas.
- Nonroad Mobile (Figure 40) sources were forecast to impact O_3 across all of the country with the largest impacts occurring in urban and agricultural areas (10-15 ppbV). The largest impacts from these sources (>30 ppb) are forecast nearshore in the Great Lakes, Mid-Atlantic, Northeast, and Florida from recreational marine vessels.
- EGU Point (Figure 41) sources were forecast to impact all of the country outside of the Pacific coast states. The largest impacts occur near the largest clusters of EGUs, which in the LADCO region are primarily in southern Illinois, Indiana, and Ohio.
- Non-EGU Point (Figure 42) sources were estimated to have the greatest impact on future year O_3 in the eastern half of the U.S., around urban areas, and near hubs of industrial activity. For example, taconite mining and related industrial activities produced an area of elevated O_3 tracer concentrations in northeastern Minnesota.

- Biogenic (Figure 43) sources were forecast to have relatively large impacts (8-20 ppbV) throughout the U.S. This sector has large impacts in much of the LADCO region, particularly in Minnesota, southern Wisconsin, and Illinois.
- Fires (Figure 44) have very large (>30 ppbV) localized impacts downwind of the source. The largest impacts forecast in the LADCO region occurred in Wisconsin, Indiana, northern Minnesota, and northern Michigan.

Table 8. MDA8 O_3 (ppbV) DV_{2023} (with WATER) CSAPR source region linkages to monitors in the LADCO 2023 simulation*

County & AIRS ID	Suffolk Co. 361030002	Fairfield Co. 90019003	Harford Co. 240251001	Sheboygan Co. 551170006	Richmond Co. 360850067	New Haven Co. 90093002	Fairfield Co. 90013007	Wayne Co. 261630019	Queens Co. 360810124	Fairfield Co. 90010017	Allegan Co. 260050003	Milwaukee Co. 550790085
STATE	**NY**	**CT**	**MD**	**WI**	**NY**	**CT**	**CT**	**MI**	**NY**	**CT**	**MI**	**WI**
2015-2017 DV	76.0	83.0	75.0	80.0	76.0	82.0	83.0	73.0	74.0	79.0	73.0	71.0
2009-2013 AVRG	83.3	83.7	90.0	84.3	81.3	85.7	84.3	78.7	78.0	80.3	82.7	78.3
2009-2013 MAX	85.0	87.0	93.0	87.0	83.0	89.0	89.0	81.0	80.0	83.0	86.0	82.0
2023 AVRG	**71.6**	**71.4**	**71.0**	70.5	70.9	69.9	69.8	68.3	69.2	68.9	68.8	63.6
2023 MAX	**73.1**	**74.2**	**73.3**	**72.8**	**72.4**	**72.6**	**73.7**	70.3	**71.0**	**71.2**	**71.5**	66.6
IL	0.65	0.67	0.85	14.93	0.86	0.43	0.72	2.32	0.72	0.39	19.25	13.36
WI	0.24	0.20	0.24	9.10	0.31	0.24	0.24	1.03	0.37	0.25	1.84	11.75
IN	0.76	0.83	1.36	6.19	1.00	0.47	0.97	2.46	0.68	0.45	6.91	4.63
OH	1.75	1.58	2.83	1.17	2.24	1.12	1.84	3.81	1.88	1.05	0.19	0.77
MI	0.96	0.60	0.77	1.85	1.03	0.67	0.68	19.56	1.22	0.48	3.35	1.81
MN	0.16	0.14	0.13	0.24	0.13	0.17	0.15	0.30	0.16	0.17	0.11	0.35
IA	0.19	0.16	0.23	0.45	0.25	0.15	0.16	0.44	0.25	0.11	0.74	0.70
MS	0.39	0.37	0.60	1.44	0.51	0.28	0.39	0.92	0.38	0.22	2.59	0.83
AR	0.14	0.15	0.21	0.62	0.16	0.10	0.15	0.32	0.11	0.08	1.92	0.43
LA	0.11	0.10	0.18	0.83	0.16	0.07	0.10	0.21	0.13	0.04	0.66	0.60
TX	0.57	0.45	0.77	1.76	0.77	0.39	0.44	1.13	0.59	0.31	2.40	1.10
OK	0.34	0.22	0.38	1.09	0.41	0.24	0.22	0.67	0.34	0.17	1.42	0.74
KS	0.19	0.14	0.24	0.49	0.24	0.13	0.14	0.46	0.19	0.09	0.77	0.31

NE	0.12	0.08	0.14	0.07	0.15	0.09	0.08	0.19	0.13	0.06	0.17	0.06
OTC[1]	0.08	0.16	0.01	0.00	0.05	0.28	0.19	0.00	0.40	0.11	0.00	0.00
CT	0.59	3.54	0.00	0.00	0.25	6.43	4.13	0.00	0.51	8.70	0.00	0.00
NY	17.30	14.66	0.16	0.03	6.99	14.61	13.24	0.06	13.18	16.64	0.00	0.02
NJ	8.42	7.35	0.06	0.00	10.57	5.45	6.60	0.00	8.13	6.07	0.00	0.00
PA	6.18	6.20	4.43	0.43	9.83	5.19	6.04	0.17	6.53	4.90	0.05	0.29
DE	0.19	0.37	0.04	0.00	0.44	0.33	0.32	0.00	0.35	0.16	0.00	0.00
MD	1.07	1.88	19.49	0.03	1.69	1.35	1.55	0.02	1.38	1.04	0.01	0.02
DC	0.04	0.08	0.64	0.00	0.06	0.05	0.06	0.00	0.05	0.04	0.00	0.00
WV	0.78	1.10	2.72	0.64	1.61	0.59	1.06	0.21	0.98	0.67	0.11	0.49
VA	0.93	1.74	4.58	0.12	1.66	1.25	1.38	0.15	1.43	1.20	0.04	0.11
SE[2]	0.84	1.25	1.77	1.04	1.62	0.69	1.23	0.87	0.96	0.74	1.76	0.82
KY	0.52	0.81	1.59	0.87	0.95	0.33	0.92	0.66	0.44	0.36	0.60	0.70
WRAP[3]	0.96	0.62	0.91	1.11	1.01	0.67	0.62	1.29	0.96	0.53	1.09	0.92
CNMX	1.76	1.35	0.79	0.64	1.54	1.66	1.34	3.14	1.72	1.64	0.53	0.73
OFFSHORE	2.17	2.97	3.48	0.76	1.92	4.36	3.02	0.36	2.23	1.52	0.45	0.54
TRIBAL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FIRE	0.28	0.33	0.42	0.66	0.37	0.21	0.33	0.43	0.24	0.20	0.91	0.33
ICBC	18.59	17.07	15.52	16.61	16.87	17.80	17.34	20.10	17.98	17.05	12.04	15.09
BIOG	4.18	4.04	5.31	7.19	5.10	3.95	3.98	6.86	4.40	3.29	8.73	5.94

[1] Includes: ME, NH, VT, MA, RI; [2] Includes: NC, SC, TN, GA, AL, MS, FL; [3] Includes: NM, AZ, CO, UT, NV, CA, WY, MT, ND, SD ID, WA, OR

* Yellow shading indicates values >= 0.70 ppb (1% of the NAAQS), orange shading indicates values >= 1.0 ppb

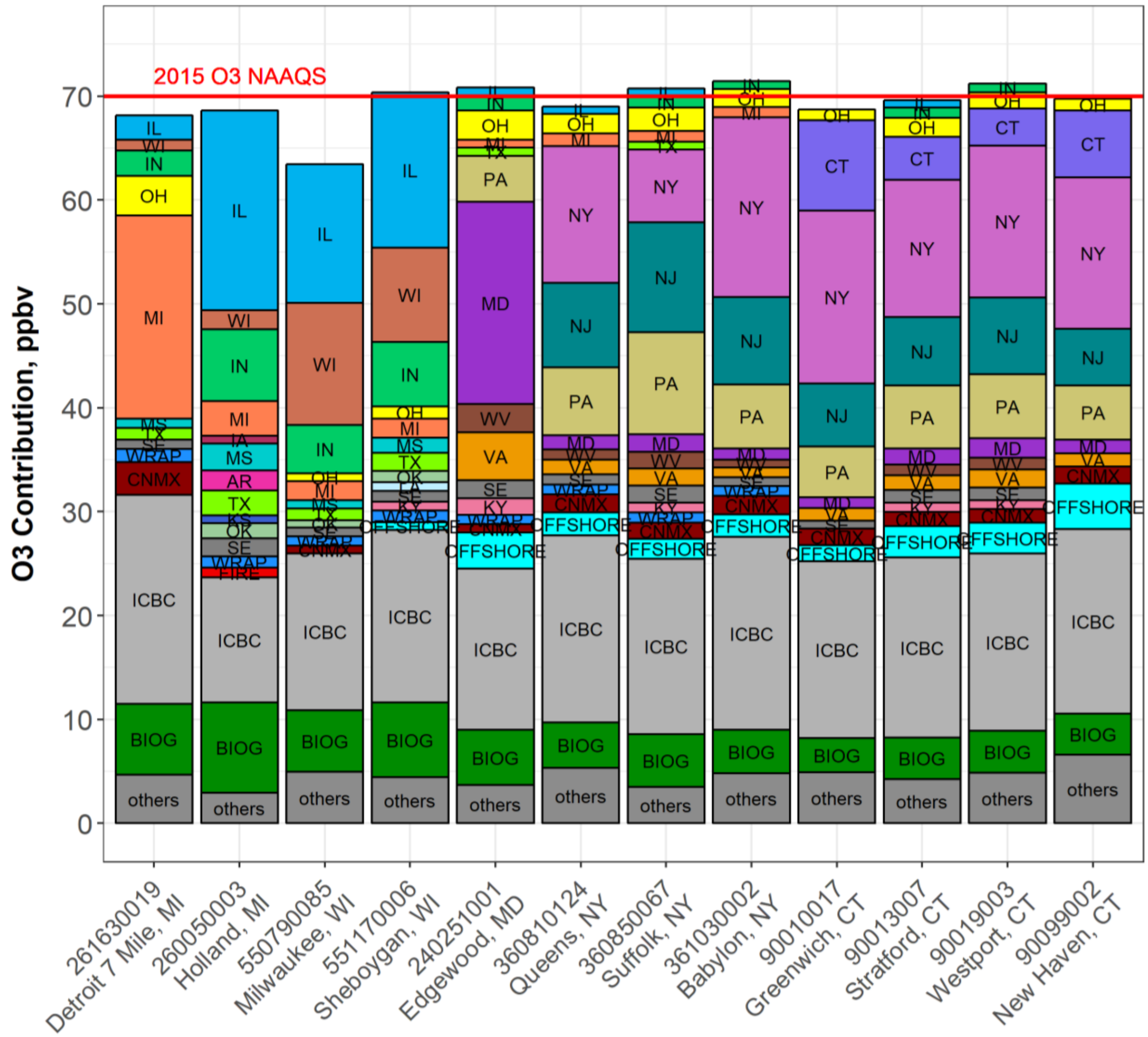

Figure 24. MDA8 O_3 (ppbV) (with WATER) source region contributions to DVs_{2023} at key monitors in the LADCO 2023 simulation

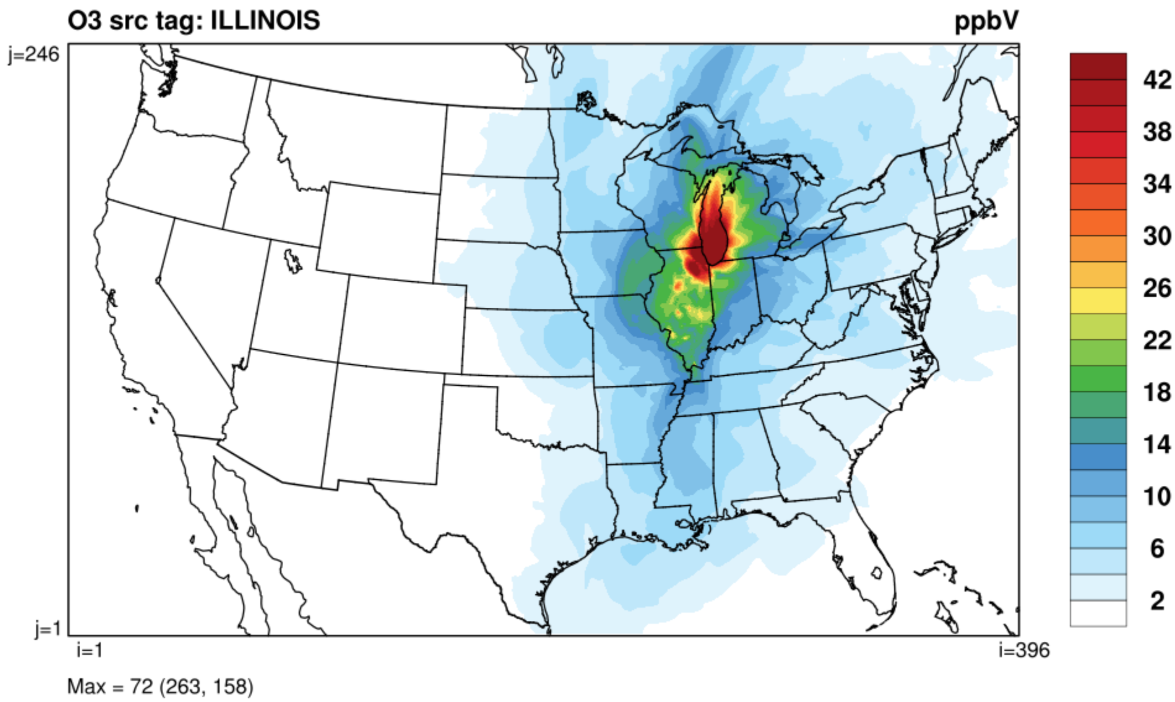

Figure 25. Ozone season maximum CAMx APCA O_3 tracers – Illinois

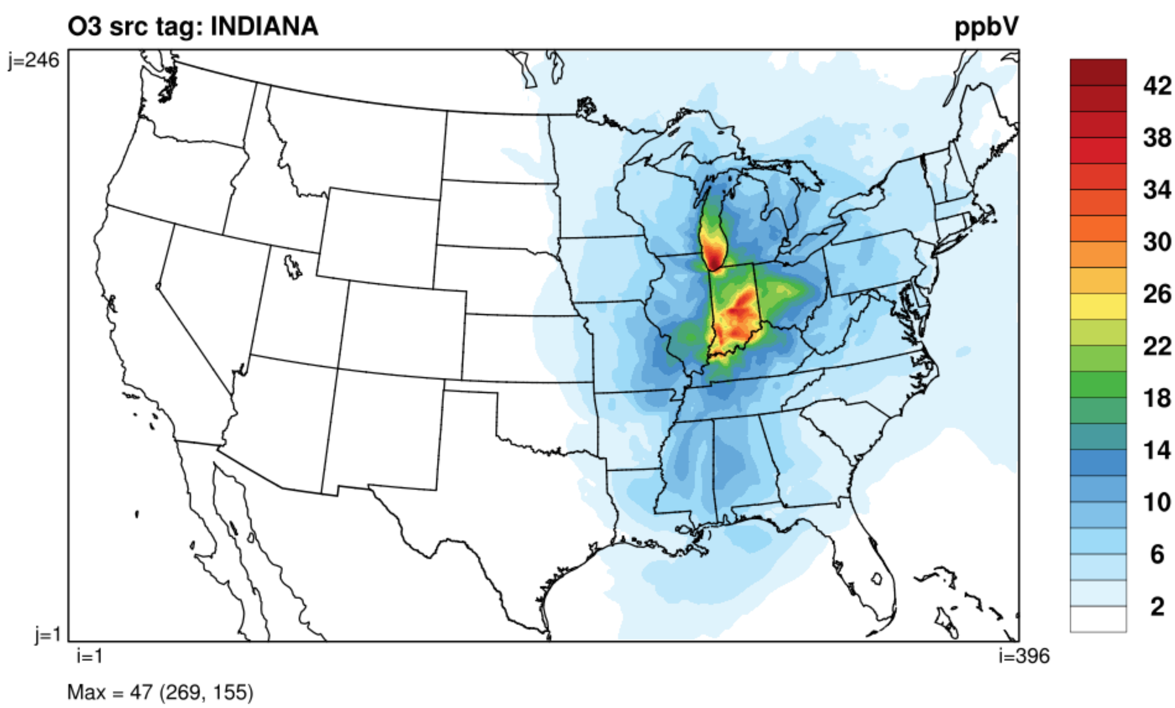

Figure 26. Ozone season maximum CAMx APCA O_3 tracers – Indiana

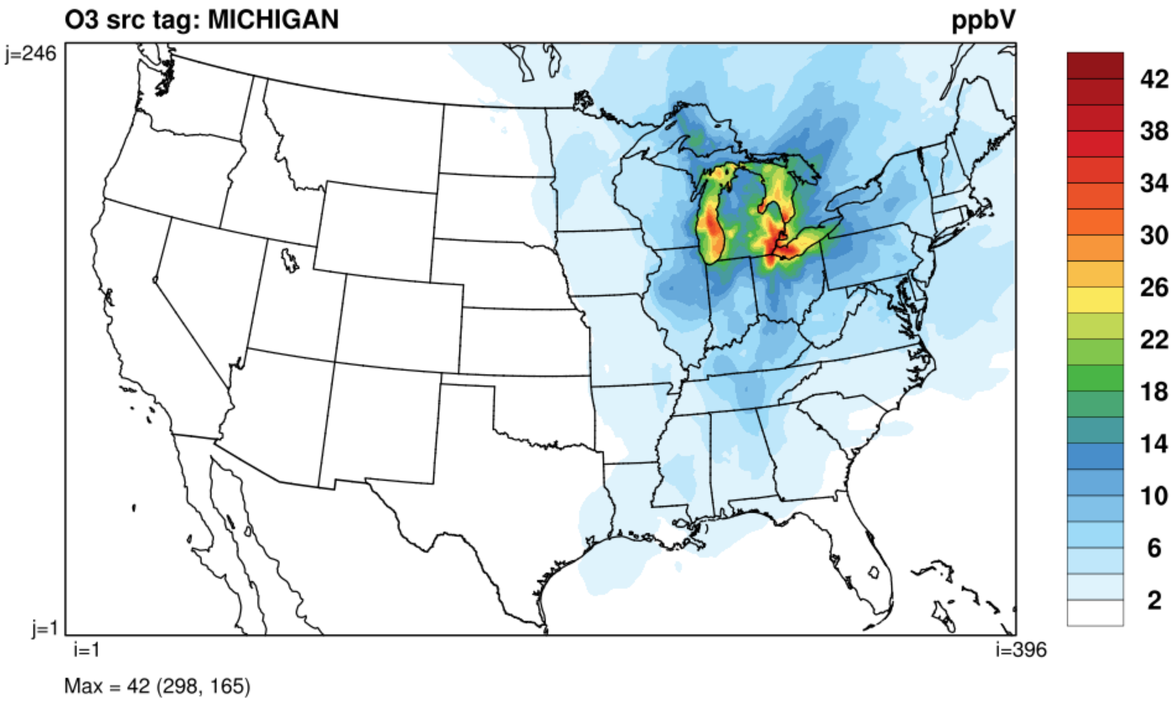

Figure 27. Ozone season maximum CAMx APCA O_3 tracers – Michigan

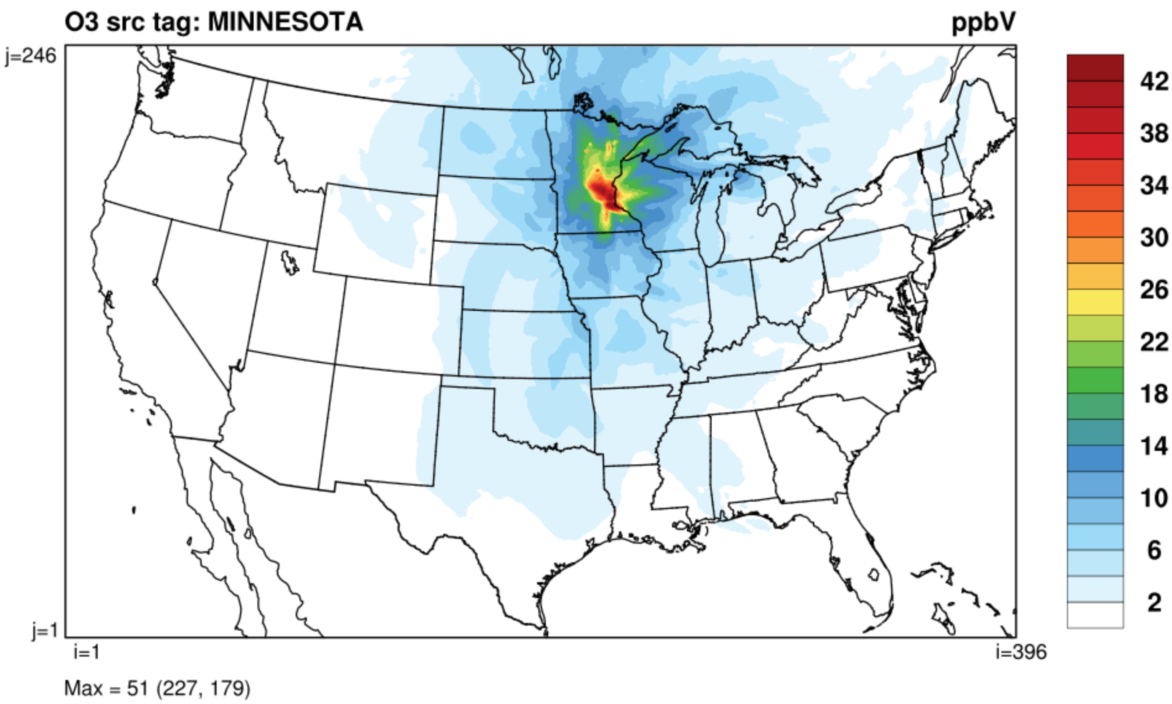

Figure 28. Ozone season maximum CAMx APCA O_3 tracers – Minnesota

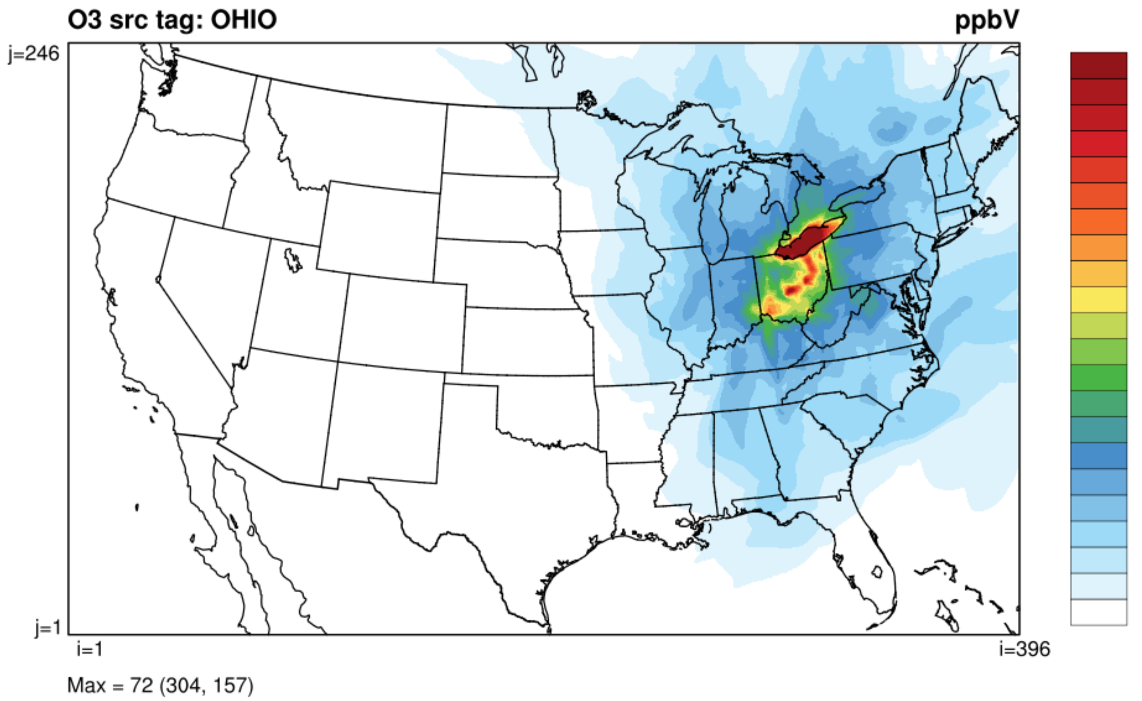

Figure 29. Ozone season maximum CAMx APCA O_3 tracers – Ohio

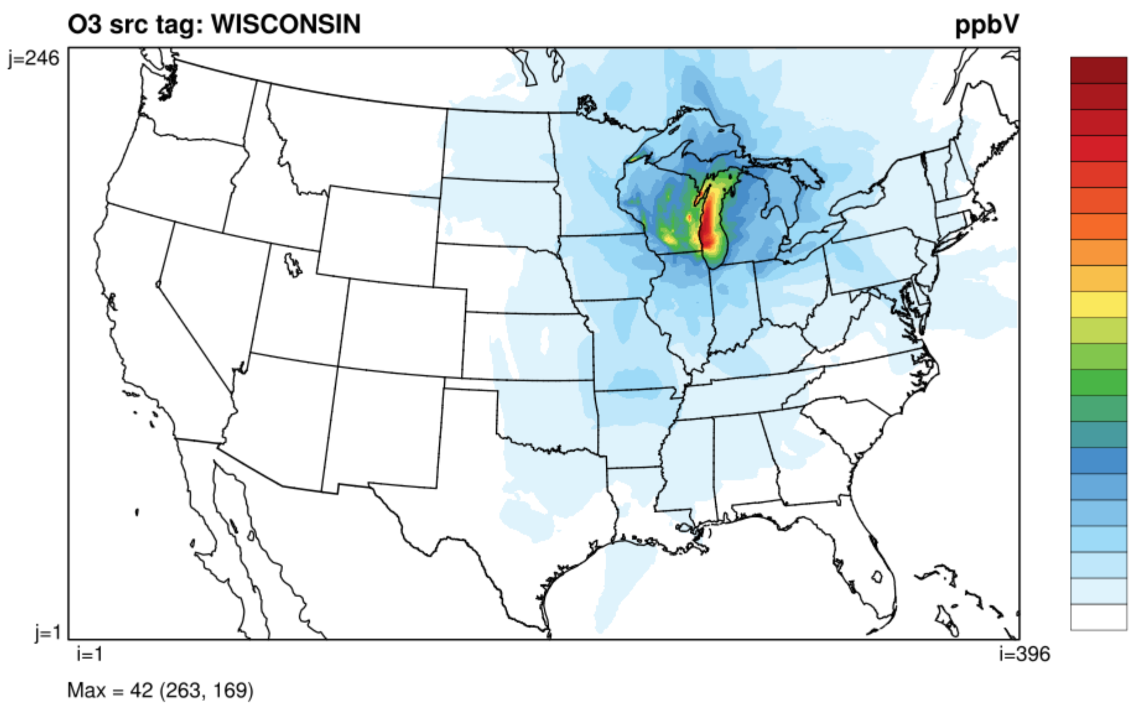

Figure 30. Ozone season maximum CAMx APCA O_3 tracers – Wisconsin

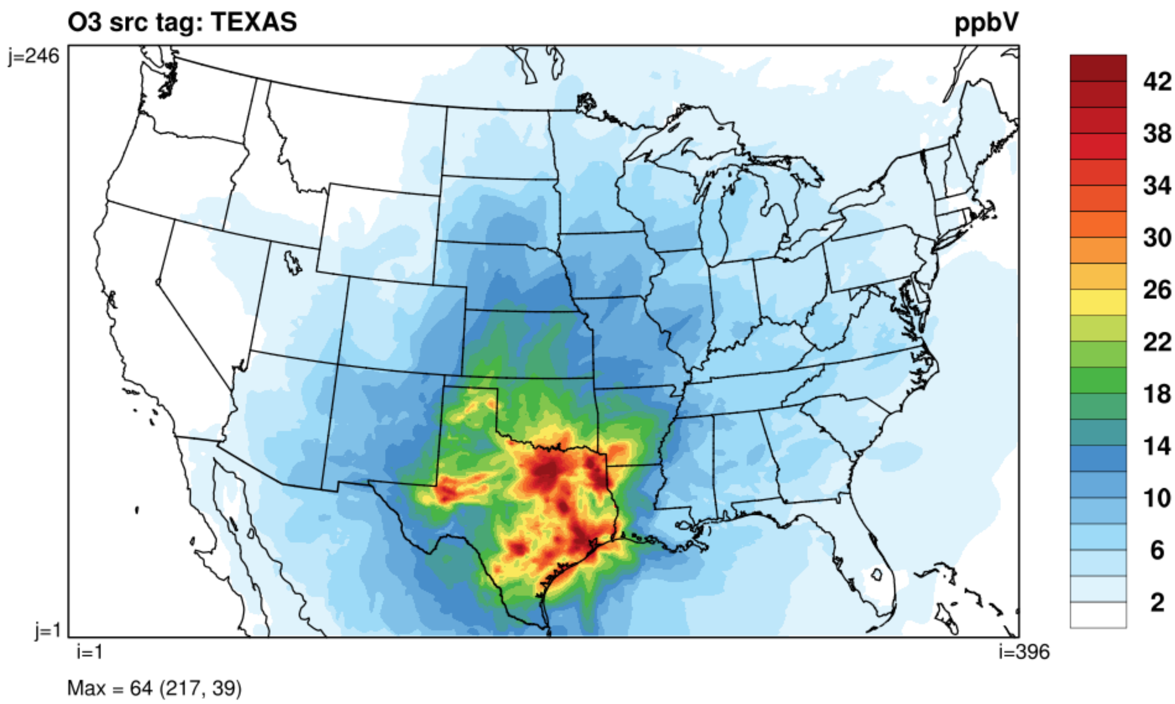

Figure 31. Ozone season maximum CAMx APCA O_3 tracers – Texas

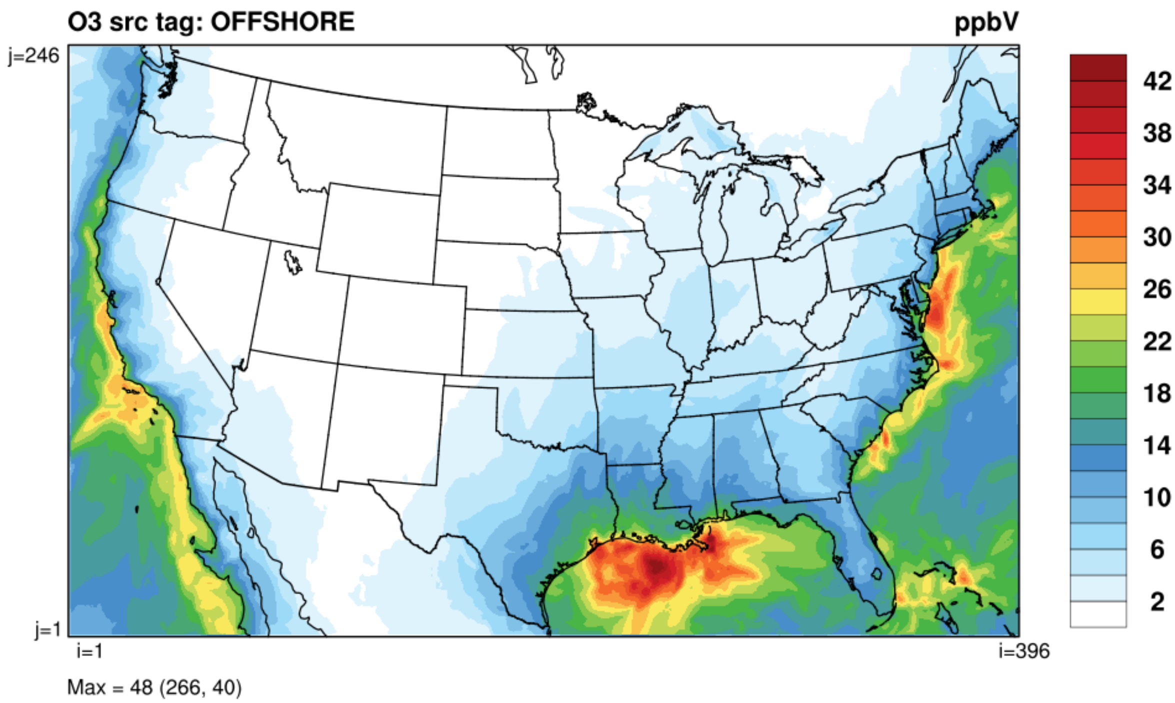

Figure 32. Ozone season maximum CAMx APCA O_3 tracers – Offshore